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CCSDS - SFCG

EFFICIENT MODULATION METHODS STUDY

AT NASA/JPL

PHASE 3: END-TO-END SYSTEM PERFORMANCE

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SUMMARY

This report contains results from Phase 3 of the *CCSDS - SFCG Efficient Modulation Methods Study* conducted at the Jet Propulsion Laboratory (JPL). Simulations were used to measure the end-to-end performance of a telemetry data transmission and capture system for Category A missions. Included in the document are descriptions of the simulation system (Section 2), system performance measurements (Section 3), and the conclusions and recommendations (Section 4).

With increasing RF spectrum congestion, it is imperative that users take immediate steps to minimize their data transmission bandwidth. This implies filtering signals prior to radiation. After reviewing several filtering locations, JPL concluded that baseband filtering was the only practical method. However, baseband filtering of a phase modulated signal introduces discrete components into the RF spectra. Phase 3 study results demonstrate that a significant increase in RF spectrum efficiency can be obtained using baseband filtering if these spectral spikes can be tolerated.

All system performance data in Section 3 are obtained by simulating a complete data transmitting and receiving system. Bit-Error-Rate, RF Spectra, and Power Containment plots are provided. Non-ideal data and system parameters are included in simulation models to make the results as realistic as possible.

In addition to the traditional phase modulation methods, MSK, GMSK, and FQPSK modulation types are investigated. FQPSK-B is a proprietary modulation technique of Dr. Kamilo Feher. GMSK and FQPSK are significantly more bandwidth-efficient than any of the traditional phase modulation methods and are the recommended types for high data rate systems. FQPSK and GMSK both employ baseband filtering.

This report concludes by developing five separate mission classifications. Missions are assigned to a class depending upon their requirements. A modulation method is recommended for each class. Recommended modulation types are the *most bandwidth-efficient feasible*, given the class's requirements.

Readers interested solely in Phase 3 study results can skip directly to Section 4.

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This document could not have been published without the heroic efforts of three persons: Ann [Nancy] Schweiner, Anthony [Tony] Sedor and Roy Halton.

Tony and Roy spent countless hours preparing the diagrams and plots found in this report. As professional graphic artists, their high standards are reflected in the many figures contained in the document.

A very special thanks is due Nancy for her professionalism, patience, and quality standards. In addition to proofreading this Phase 3 report, Nancy edited each figure and translated it from a graphics application to this word processing program. Anyone who has attempted such a chore will immediately understand the task's magnitude and the frustration which most certainly follow. It was an ordeal. Whatever else can be said about modern computer application programs, *they are not friendly*.

The authors would also like to thank Dan Bathker, Franz Borncamp, Robert Petrie, and many others for their constructive suggestions and ideas. In the end, this document represents the work of many people.

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EFFICIENT MODULATION METHODS STUDY AT NASA/JPL

1.0 INTRODUCTION

At the 12th annual meeting of the Space Frequency Coordination Group (SFCG-12), held during November 1992 in Australia, the SFCG requested that the Consultative Committee on Space Data Systems (CCSDS) RF and Modulation Subpanel study and compare various modulation schemes (SFCG Action Item 12-32). Since then, representatives from the European Space Agency (ESA), NASA's Goddard Space Flight Center (GSFC), NASA's Jet Propulsion Laboratory (JPL), and New Mexico State University (NMSU) have completed a three-phase study. This document summarizes the results found in Phase 3 of the *CCSDS-SFCG Efficient Modulation Methods Study* [hereinafter termed the *Efficient Modulation Methods Study*] by the JPL team.

This study was motivated by the realization that frequency bands are becoming commodities auctioned to the highest bidder. Additionally, the number of users in bands, traditionally used by space agencies, has burgeoned. The result has been increased congestion and more frequent reports of interference. It is becoming necessary for regulatory organizations to scrutinize requests for frequency *Assignments* carefully to ensure that only those systems designed to use the minimum *necessary* bandwidth are granted protection or licenses. This study was intended to determine the minimum RF bandwidth *required* for a space data system transmitting digital data. The Phase 3 study objective is to *pack many more users in a frequency band, particularly at 2 and 8 GHz*, while avoiding mutual interference between spacecraft operating on adjacent frequencies.

Given the existing set of frequency allocations, the potential for interference increases directly with the data rate and the number of such missions flying. It was shown during Phases 1 and 2 that, absent bandwidth control, spacecraft transmitting high telemetry rates require RF bandwidths many times their data rates. Expanded frequency allocations are unlikely in the foreseeable future. Therefore, filtering to restrict RF spectrum utilization is becoming mandatory. But, the losses incident to such filtering and the susceptibility to interference resulting from band limiting are also important. Phase 3 of the *Efficient Modulation Methods Study* seeks to minimize the transmitted RF bandwidth while maintaining acceptable system losses and reasonable interference immunity.

> While these results are generally applicable to all digital communications systems employing the modulation types covered, this study's emphasis was on telemetry transmissions from Category A missions (distance # 2 x 10^6 km) and not on deep space (Category B) missions.

1.1 PRIOR STUDIES

Phase 1 and Phase 1b were concerned with identifying the several modulation methods commonly used by space agencies and determining the bandwidth needed by each. The initial two papers [1, 2] considered nine modulation schemes including:

- PCM/PSK/PM Square
- PCM/PSK/PM Sine
- PCM/PM/NRZ
- PCM/PM/Bi-N
- BPSK/NRZ
- BPSK/Bi-N
- QPSK
- OQPSK
- GMSK

Phase 2 [3] demonstrated that an unfiltered frequency spectrum rolls off very slowly, particularly with non-ideal data (2% *Data Asymmetry*, 10% *Data Imbalance*). Transmitting systems with asymmetric data and non linear elements (modulators, multipliers, and power amplifiers) distort the signal, exacerbating the problem. Such systems produce a transmitted RF spectrum with significant energy at frequencies many multiples of the data rate (R_B) from the center frequency.

Phase 2 considered the benefits of baseband filtering prior to transmission. Several alternative filter types and locations were considered and the results compared using PCM/PM/NRZ modulation. It was noted that post Power Amplifier (PA) filtering was theoretically the most effective method for limiting unwanted emissions in the RF spectrum. However, such filters suffer from the disadvantages of substantial weight, transmitter power loss, and comparatively high cost. These disadvantages result in a reluctance by flight projects to limit their RF bandwidth requirements. Moreover, post PA filters have to be tailored to the telemetry data rate <u>and</u> the RF frequency of each mission. Similar faults were found with filters placed at some intermediate frequency (i.f.).

Phase 2 concluded [4] that baseband filtering produced the best compromise between simplicity, flexibility, weight, and cost. Four filter types were investigated using PCM/PM/NRZ modulation: Butterworth, Bessel, Raised Cosine, and Square Root Raised Cosine. Raised Cosine filters were discarded because their output amplitude varied the data's transition density. The remaining filter types survived and were tested again in Phase 3. Square Root Raised Cosine filters produced the best roll-off in the RF spectrum, when compared to the unfiltered case, although both Butterworth and Bessel filters provided reasonable attenuation. It was shown that spectrum shaping, in combination with a bandwidth-efficient modulation type, had the potential for increasing frequency band utilization by several times.

1.2 PHASE 3 OBJECTIVES

Phase 3 is concerned with the space data system's end-to-end performance. Modulation methods and filtering, which significantly reduce RF spectrum requirements, are of little value if captured data contain so many errors that it becomes unusable. Here, the objective is to develop guidelines for digital data transmission/receiving systems producing the minimum RF spectrum width while having reasonable end-to-end losses.

1.3 PHASE 3 SCOPE OF WORK

Phase 3 studies examine modulation types currently used or planned by the international space agencies. It is constrained to minimize changes to transmitting and receiving equipment. Such restrictions undoubtedly limit the performance obtained to sub-optimal. However, the large investment which space agencies have in their current data systems dictates a slow and orderly transition to more sophisticated techniques.

This Phase 3 Study Explores the Feasibility of Baseband Filtering Only.

1.4 PHASE 3 MODULATION TYPES

Phase 2 examined modulation methods currently used or planned by the CCSDS Space Agencies. Except for PCM/PSK/PM *Sine* and PCM/PSK/PM *Square*, all modulation types studied in Phase 2 are retained in this Phase 3 study. The two subcarrier modulation types were dropped because they were not found to be bandwidth-efficient unless the Subcarrier-to-Symbol-Rate ratio was kept at a value of 4 or lower. Frequently, space agencies have used higher Subcarrier-to-Symbol-Rate ratios, some of which exceed a value of 200! Table 1.4-1 lists the Phase 3 modulation types.

Table 1.4-1: Phase 3 Modulation Types

Modulation Name	Modulation Type	Filter Types Used
PCM/PM/NRZ	Phase	Butterworth, Bessel, Square Root Raised Cosine
PCM/PM/Bi-N	Phase	Butterworth, Bessel, Square Root Raised Cosine
BPSK/NRZ	Phase	Butterworth, Bessel, Square Root Raised Cosine
BPSK/Bi-N	Phase	Butterworth, Bessel, Square Root Raised Cosine
QPSK	Phase	Butterworth, Bessel, Square Root Raised Cosine
OQPSK	Phase	Butterworth, Bessel, Square Root Raised Cosine
MSK	Frequency [2]	Sinewave Pulse Shaping
GMSK	Frequency [2]	Gaussian Pulse Shaping
8-PSK	Phase	Butterworth, Bessel, Square Root Raised Cosine
FQPSK-B	Phase [1]	Proprietary Design

NOTES:
1. **Non-Constant Envelope**
2. **Continuous Phase Modulation**

1.5 PHASE 3 STUDY APPROACH

Phase 3 examines the performance of the modulation methods listed in Table 1.4-1 when combined with alternative baseband filtering techniques. Performance was evaluated by measuring the increase in E_B / N_0 required to maintain the data Bit-Error-Rate (BER) at a constant level. Most international space agency missions now adhere to CCSDS Recommendations for Space Data System Standards (Blue Books). This implies a packetized format which must operate at very low BERs (BER # 1×10^{-6}). Such low BERs require error detecting-correcting codes operating at very low symbol energies. When the received signal's E_S / N_0 falls too low and the Symbol-Error-Rate (SER) rises, the decoder may be incapable of correcting errors resulting in deleted telemetry frames.

For the CCSDS recommended code (convolutional: R = ½, k = 7; concatenated with a Reed-Solomon 223/255 block code) the required SER lies between 1×10^{-2} and 1×10^{-3}. Therefore, the criterion applied to Phase 3 is that of the SER # 1×10^{-3} which results in a BER # 1×10^{-7} when using CCSDS recommended concatenated coding. Phase 3 studies made use of uncoded data.

Phase 3 involved the following steps for the several modulation methods and filter types:

- Determining which transmit system characteristics affect the RF spectrum
- Optimizing each baseband filter's bandwidth
- Measuring the transmitted RF spectrum's width at several levels
- Quantifying end-to-end system losses
- Calculating the increased RF spectrum utilization
- Evaluating modulation types according to interference susceptibility
- Recommending modulation methods and filtering standards to both CCSDS and SFCG

1.5.1 Simulated Measurements

Constructing a real hardware system to make the necessary measurements was too time consuming, expensive, and beyond the scope of this Phase 3 study. As in phase 2, all measurements were made using simulations. FQPSK-B simulations received a cursory hardware validation test.

1.5.2 Evaluation Criteria

Phase 3 searched for those modulation methods and baseband filter combinations providing the narrowest RF spectrum width with acceptable end-to-end losses. Improving the RF bandwidth efficiency of high data rate systems provides the maximum return-on-investment. Therefore, all recommended systems had to be capable of operating at high to very high digital data rates. Moreover, the recommended systems were required to be compatible with existing spacecraft transmitters and earth station receivers.

Evaluation involved studying BER vs E_B / N_0 plots to select a filter bandwidth as narrow as possible while introducing acceptable Filtering Losses (Inter-Symbol Interference [ISI] and Mismatch). Spectra were plotted for the selected filters to assess the improvement in bandwidth efficiency. Finally, Power Containment curves were generated to show occupied bandwidth.

1.6 REPORT ORGANIZATION

This *CCSDS - SFCG Efficient Modulation Methods Study* Phase 3 report is divided into four sections. Following these introductory remarks, Section 2 describes the simulation system used to make end-to-end performance measurements. Section 2 also discusses filter location selection and filter bandwidth optimization. Section 3 contains study results. Bit-Error-Rate (BER) curves, RF spectrum, and Power Containment plots are presented for each modulation type. Section 3 contains the data needed for the conclusions found in Section 4. Section 4 summarizes this study and sets forth both conclusions and recommendations. Persons interested only in the Phase 3 study results need only read Section 4.

2.0 SYSTEM CONFIGURATION

Efficient Modulation Methods Study, Phases 1 and 2 (References 1, 2, and 3), provided several important system configuration results including:

- Subcarrier modulation should be avoided whenever possible.
- Non-ideal data and transmitting system components materially affect the RF spectrum.
- Baseband filtering tends to reduce the detrimental effects of asymmetrical data waveforms.
- Baseband filtering can significantly reduce the transmitted RF spectrum's width.
- Raised cosine baseband filters are not useful with an NRZ digital data source.
- Amplitude modulation is detrimental to the phase modulated RF spectrum's width.

These findings are incorporated in the Phase 3 study. While the Phase 3 transmitting system's block diagram is similar to that in Phase 2, there are significant differences. Additionally, a receiving system was added to complete the end-to-end evaluation. Figure 2.1-1 is a system block diagram. This section summarizes the simulator's and communications system's characteristics.

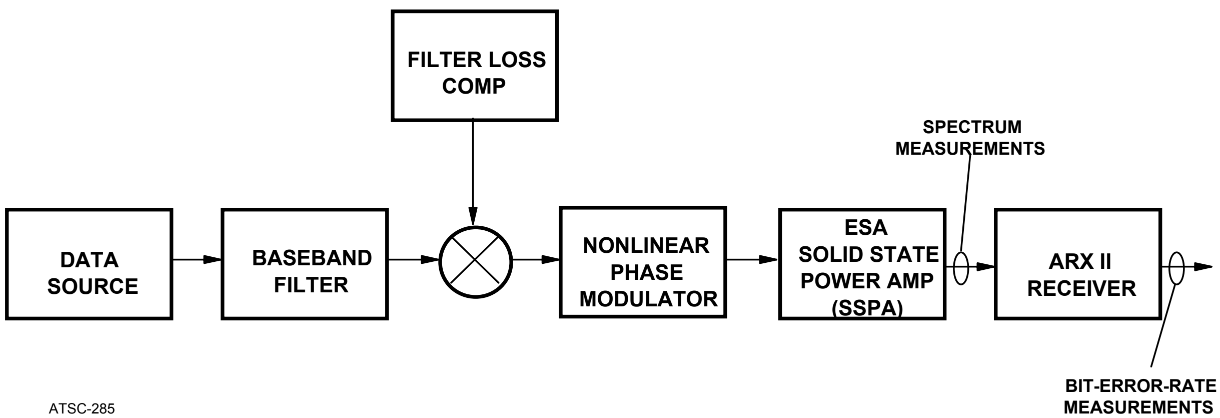


Figure 2.1-1: Simulated System Block Diagram

2.1 SIMULATION SYSTEM

All Phase 3 measurements were made by simulation using Cadence Design Systems Inc. Signal Processing Work system (SPW) running on a Sun Ultra Spark 2, 4-processor, workstation. A study was undertaken to optimize the simulator's operating parameters and a Fast Fourrier Transform (FFT) bin size of 1 Hz was selected. The corresponding resolution bandwidth is 1.33 Hz. All spectra contained in this study are plotted at that resolution.

As in Phase 2, the frequency scale is specified in units of baseband data rate, R_B. R_B corresponds to the frequency span, f_S, between RF spectrum nulls resulting from the data bit period, T_B. Thus,

$$f_S = R_B = \frac{1}{T_B} \quad where{:}\ T_B\ is\ the\ Data\ Symbol's\ Bit\ Period. \tag{2-1}$$

R_B, rather than the R_S, is used to permit easy comparison of the bandwidths required by the several modulation types. No error-detecting error-correcting coding is used in this study so $R_B = R_S$. When comparing spectrum plots for PCM/PM/NRZ and PCM/PM/Bi-N modulation using the same data rate, the latter requires approximately twice the spectrum width of the former. This is so because a Bi-N modulating waveform is created by the modulo-2 addition of a baseband NRZ digital data stream with a synchronous double frequency square wave signal. Thus, each baseband data bit comprises both a +1 and -1 symbol, doubling the rate.

Signal amplitude (power) is measured in dB relative to the data sideband's peak. Modulation types are normalized with respect to the peak data sideband power irrespective of whether they are residual or suppressed carrier systems. Since the required spectral width is determined entirely by the modulation sidebands, the spectrum efficiency of a modulation-filter combination can be determined by measuring sideband power as a function of R_B. Spectrum plots label the carrier frequency f_C as $R_B = 0$.

2.1.1 Data Source

The Data Source is capable of generating either Non-Return-to-Zero (NRZ) or Bi-Phase (Bi-N) data formats. The latter format is often termed *Manchester* coding. Only the NRZ data format was used during Phase 2 to facilitate a simple comparison of baseband filter types. In Phase 3, both types of data formats are employed.

Except for the reference case (Section 3.1) employing both ideal and non-ideal data, all system performance evaluations were made using non-ideal data. In Phase 2, non-ideal data meant:

Data Asymmetry (ratio duration of +1 to duration of -1) = ± 2%
Data Imbalance (difference of "+1s" to "-1s", mark-to-space) = 10%

These values represented the maximum deviations from ideal data which technical studies, undertaken by the CCSDS RF and Modulation Subpanel (Subpanel 1E), show should be permitted. They are independent of the duration of the asymmetry or imbalance.

A new modulator was developed for the Phase 3 study. Termed the *Universal Phase Modulator* (UPM), this device embodies a Digital-to-Analog (D/A) converter at its input. The D/A converter contains a 3-bit register to hold the telemetry data. Data is clocked into the register at uniform intervals. Re-clocking at the modulator's input removes *Data Asymmetry* introduced by the stray capacitance and inductance in lines connecting the spacecraft's data system to the modulator. Therefore, the Phase 3 study used the following data characteristics.

- Data Asymmetry (ratio duration of +1 to duration of -1) = ± 0%
- Data Imbalance (difference of "+1s" to "-1s", mark-to-space) = 10%
  - For this study the Probability of a Mark ($-_M$) = 0.55

2.1.2 Filtering

Phase 2 demonstrated that significant RF spectrum limiting was obtained using baseband filtering. Except for the Raised Cosine filter whose output amplitude decreased at high transition densities, Phase 3 filter types are identical to those used in Phase 2. Raised Cosine filters were excluded from the Phase 3 study.

During Phase 2, alternative filter locations were considered. These locations included:

- Filtering After Power Amplification (post PA filtering)
- Filtering at a Transponder Intermediate Frequency (i.f.)
- Filtering at Baseband

2.1.2.1 Filtering After Power Amplification

Post Power Amplifier (PA) filtering is very attractive to Spectrum Managers because all unwanted emissions, which are outside the filters passband, will be eliminated. Theoretically, this filter location provides maximum control over emissions. However, it would be difficult for post PA filtering to improve the RF spectrum utilization efficiency of most space missions.

Experts state that either stripline or waveguide bandpass filters are generally used in microwave applications. For reasonable insertion losses (# 6 dB), such filters are constrained to bandwidths ranging from 1.5% - 2% of the transmitted frequency. For stripline filters, this corresponds to a *Loaded Q* (Q_L) of 50 - 70. Available materials limit the *Unloaded Q* (Q_U) to values of about 250 resulting in insertion losses on the order of 6 dB! Additional small losses result from filtering modulation sidebands beyond the filter's passband. Similar values of Q_L are obtainable with waveguide filters. While this filter type can have a somewhat lower insertion loss, they tend to be very large and heavy.

Assuming the best case, Q_L = 70 and a transmitting frequency of 2250 MHZ, the narrowest practicable filter bandwidth would be 32 MHZ! With convolutionally encoded data, BPSK/NRZ modulation, and a filter whose symbol Bandwidth • Time product (BT_S), is 2; the *minimum usable data rate* is 4 Mb/s (8 Mb/s if data is not convolutionally encoded). The vast majority of Category A missions which could benefit from filtering have far lower data rates.

JPL personnel concluded that post PA filtering cannot significantly increase the number of Category A missions operating in a frequency band and this study did not include that filtering option.

2.1.2.2 Filtering at a Transponder Intermediate Frequency (i.f.)

Filtering at i.f. is attractive because the filter operates at low power levels, does not reduce transmitted RF power, can be small and lightweight, and does not introduce the spectral spikes inherent in baseband phase domain filtering. However, the feasibility of this option depends upon the transponder's design.

The transponder for JPL's Cassini mission modulates at the RF transmitting frequency (i.e., 8.4 GHz); therefore, the remarks concerning Q_L set forth in Section 2.1.2.1 above apply and i.f. filtering is impractical. If a transponder modulates at lower frequencies and translates the signal to the RF frequency, then some filtering may be possible.

For i.f. frequencies in the 100 MHZ range, Surface Acoustic Wave (SAW) filters provide good performance. If a $Q_L = 100$ is achievable with a $BT_S = 2$ and the i.f. frequency is only 100 MHZ, then the minimum filter bandpass will be 1 MHZ corresponding to an uncoded symbol rate of 250 ks/s. This is probably a sufficiently low data rate if it was the only impediment.

Effective spectrum management requires that the i.f. filter's bandwidth be adjusted to each mission's maximum telemetry data rate. JPL has found that transponder modifications are very expensive and may introduce performance problems. Transponders must be thoroughly tested to ensure that spurs and leakage are controlled and well understood. Failure to do so can result in *lockup*, with the result that all communication to the spacecraft becomes impossible. Modifying an i.f. filter for a new data rate may require full retesting of the transponder.

There is one additional constraint. Many space missions utilize turnaround ranging having code rates higher than the telemetry data rate. In such cases, i.f. filtering requires that the bandwidth be adjusted to the wider bandwidth signal, even if it is only present for a small fraction of the time. This was deemed undesirable from implementation and spectrum management viewpoints.

For all of these reasons, i.f. filtering was not found to significantly increase the number of Category A missions operating in a frequency band and this study does not include an i.f. filtering option.

2.1.2.3 Filtering at Baseband

JPL's *Efficient Modulation Methods Study* was limited to this option. Baseband filtering is attractive because the filters operate at low power, are lightweight, do not reduce transmitted RF power, and are small and simple (lowpass rather than a bandpass). Moreover, since they precede the phase modulation process, a second input bypassing the filter can be provided for the turnaround ranging signal.

Baseband filtering of phase modulated signals suffers from the disadvantage of introducing spikes into the RF spectrum. These spikes are clearly evident in the spectra found in Section 3 of this report. Pre-distorting the modulation waveform can reduce the spike amplitude near f_C; however, their complete elimination requires use of an alternative modulation method such as Continuous Phase Modulation (CPM) or FQPSK.

Despite this limitation we have concluded that baseband filtering is the only practical method to limit the transmitted RF spectrum for the purpose of improving bandwidth efficiency. The remainder of this report discusses the performance of baseband filtered systems.

2.1.2.4 Baseband Filter Optimization

During Phase 2, no attempt was made to optimize the baseband filters for phase modulated signals. With a $BT_S = 1$, the Butterworth and Bessel filters essentially limited the PCM data to its fundamental frequency component (e.g., the rectangular waveform becomes sinusoidal in appearance). Such bandwidth restriction is likely to result in unacceptable losses.

Phase 3 included a separate study to optimize filter bandwidth. This investigation measured RF spectrum width, system performance, and system losses as a function of each filter type's BT_S product. The following parameters were measured:

- Inter-Symbol Interference (ISI) + Mismatch Losses
- Bit-Error-Rate (BER) vs Bit [Symbol] Signal-to-Noise Ratio (SNR)
- Transmitted RF Spectrum Width

Table 2.2-1 summarizes the findings of the baseband filter study.

Table 2.2-1: Optimized Baseband Filter Characteristics

Filter Type	Characteristics	ISI + Mismatch Losses [1] (dB)
Butterworth	3-Pole; $BT_S = 2$	0.2 - 1.3
Bessel	3-Pole; $BT_S = 2$	0.1 - 1.0
Square Root Raised Cosine	2000 Taps; " = 1.0; NRZ	0.4 - 0.8

NOTES:

1. **Inter-symbol interference + mismatch losses for the phase modulation types in Table 1.4-1. Losses evaluated at BER = 1 x 10^{-3}.**

Phase 2 studies disclosed that baseband filters materially improve the RF spectrum of an asymmetrical baseband modulating waveform. That is not surprising because elimination of higher order harmonics should reduce RF spectrum's width. To a great extent, baseband filters will correct data asymmetry likely to occur in high data rate systems where re-clocking of the data at the modulator's input is not possible.

Baseband filtering introduces losses from Inter-Symbol Interference (ISI) and lack of an equivalent filter in the receiver (Mismatch Losses). There are additional system losses resulting from imperfect carrier tracking and symbol synchronization. Termed *Filtering Losses* these components are tabulated in Table 4.1-1.

2.1.2.5 Spectral Spikes

Spectral spikes are an inherent result of a filtered waveform which is phase modulated on an RF carrier.[5] Spikes were evident in all filtered, phase modulated spectra contained in the *Efficient Modulation Methods Study,* Phase 2, report. Spikes can be eliminated by removing the baseband filter, relocating the filter following phase modulation or power amplification, or by selecting a new modulation type such as Continuous Phase Modulation (CPM) or FQPSK. Pre-distorting the modulating waveform can reduce, but not eliminate, spikes close to the center frequency.

2.1.3 Modulator Design

Phase Modulation (PM) is commonly used by the CCSDS Space Agencies for communication with spacecraft. While Frequency Shift Keying (FSK) and Amplitude Modulation (AM) have been used in the past, most of these spacecraft using these older methods are no longer in use. Therefore, neither of these types are considered in this study. Continuous Phase Modulation (CPM) techniques appear to offer some advantages in spectrum efficiency and have been examined as part of this study.

Phase modulators have proven a serious source of difficulty throughout the *Efficient Modulation Methods Study* because of their profound effect upon the width of the transmitted RF spectrum. A study was conducted to measure the extent of these effects.

Modulators containing non-linearities and amplitude modulation can materially increase RF spectrum's width. Every effort was made during the Phase 3 study to ensure that the simulation results accurately reflect the performance of real hardware. In furtherance of that objective, non-ideal data and component hardware models were used. Nevertheless, during Phase 3 when it was discovered that a hardware element's performance could be improved with only a simple change, that modification was incorporated.

The phase modulator is an example. Early in Phase 3, the modulator's simulation model was adopted from the Cassini mission's development program. The model accurately reflects Cassini modulator's real performance. Because Cassini's telecommunications link employs a residual carrier, its modulator operates over a comparatively restricted range. It does not need to maintain perfect phase shift vs. input voltage linearity above approximately ± 80 degrees. Additionally, amplitude variations beyond ± 80 degrees are also unimportant. For other modulation types, both non-linearities can significantly affect the RF spectrum.

2.1.3.1 Universal Phase Modulator

A simple modification to the Cassini modulator substantially eliminates both amplitude and phase non-linearities permitting the modulator to be used in QPSK and 8-PSK applications. Rather than modulating at a transmit frequency f_T . 8.4 GHz, the modulator operates at $f_T/2$. 4.2 GHz and is followed by a x 2 multiplier. The latter multiplies both the frequency and phase shift by 2 times providing the correct transmitting frequency and permitting the modulator to operate in its linear region. A block diagram of this *Universal Phase Modulator* (UPM) appears in Figure 2.1-2. The modulator is termed *Universal* because it can generate <u>all</u> phase modulation types, save OQPSK, listed in Table 1.4-1. It was used for all spectra in Section 3.

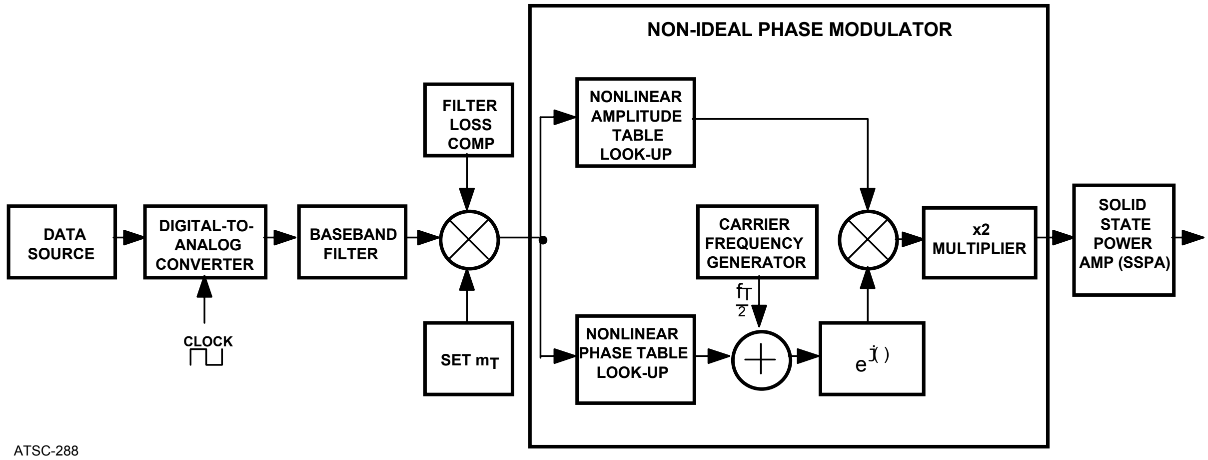


Figure 2.1-2: Universal Phase Modulator in Transmitting System

In Figure 2.1-2, the *Universal Phase Modulator* consists of the Cassini modulator and the associated analog-to-digital converter, baseband filter, summer, and x 2 multiplier. Baseband filtering is accomplished in the phase domain resulting in a constant envelope modulation.

The UPM's characteristics appear in Figure 2.1-3. It shows the UPM's phase shift to be quite linear with input voltage. Amplitude variation is about ± 0.4 dB and is slightly smaller if a frequency multiplier, rather than a squaring circuit, is used for frequency doubling.

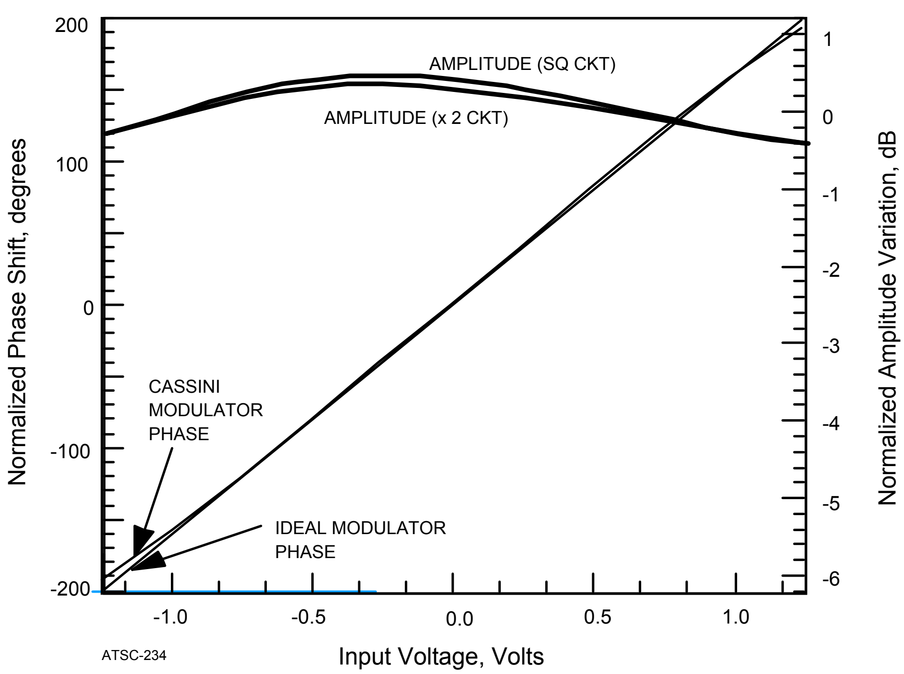


Figure 2.1-3: Universal Phase Modulator Characteristics

2.1.4 Power Amplifier

The power amplifier remains unchanged from that used in the Phase 2 study. Because of spectrum congestion and RF signal levels, the *Efficient Modulation Methods Study* is principally applicable to Category A missions (spacecraft whose distance from Earth is # 2 x 10^6 km). Category A missions typically employ Solid State Power Amplifiers (SSPAs). The simulation model embodied the characteristics of the European Space Agency's SSPA.

2.1.5 ARX II Receiver

A receiver is required to complete the communications system. The ARX II was developed by JPL's Communications Systems and Research Section. It was the research and development prototype for the Block V receiver now widely deployed throughout the Deep Space Network (DSN).

Many simulations were run throughout the development cycle of the ARX II. The ARX II simulation model, developed and verified by comparing simulation results to actual receiver measurements, has been used for this Phase 3 study.

By design, the ARX II can handle most of the modulation types shown in Table 1.4-1. Some modifications to the simulator model were required to handle 8-PSK. Since the actual hardware does not currently embody these features, the simulator's performance could not be verified by hardware tests. Figure 2.1-4 shows squaring circuits added to the ARX II receiver model which were necessary to handle 8-PSK modulation.

2.1.5.1 Symbol Synchronizer

The ARX II receiver includes a symbol synchronizer utilizing a Digital Transition Tracking Loop (DTTL). DTTL synchronizers are commonly used by space agencies. Unfortunately, the design suffers from three disadvantages. First, its performance deteriorates below an E_S / N_0 of -7 dB. Second, it has difficulty in obtaining and maintaining symbol synchronization at low symbol transition densities. Third, it does not support modulation types such as 8-PSK, MSK, GMSK, and FQPSK. For this Phase 3 study, it was necessary to employ a different type of device known as a Maximum A Posteriori (MAP) symbol synchronizer.

Preliminary studies show that MAP symbol synchronizers overcome many of the problems found with DTTL devices. Good performance can be obtained down to an E_S / N_0 = -10 dB. Synchronization can be maintained, even at low symbol transition densities. Finally, MAP synchronizers can handle MSK, GMSK, an FQPSK signals, as well as those generated by the traditional phase modulation schemes.

A MAP synchronizer was implemented in the SPW simulator for the MSK, GMSK, and FQPSK-B studies. No actual hardware for such a device exists at JPL. Therefore, the SPW model assumed ideal performance (i.e., perfect synchronization). This assumption made it impossible to quantify all of the losses for the phase modulated systems, summarized in Table 4.1-1. Further development of MAP synchronizers is recommended to determine their performance.

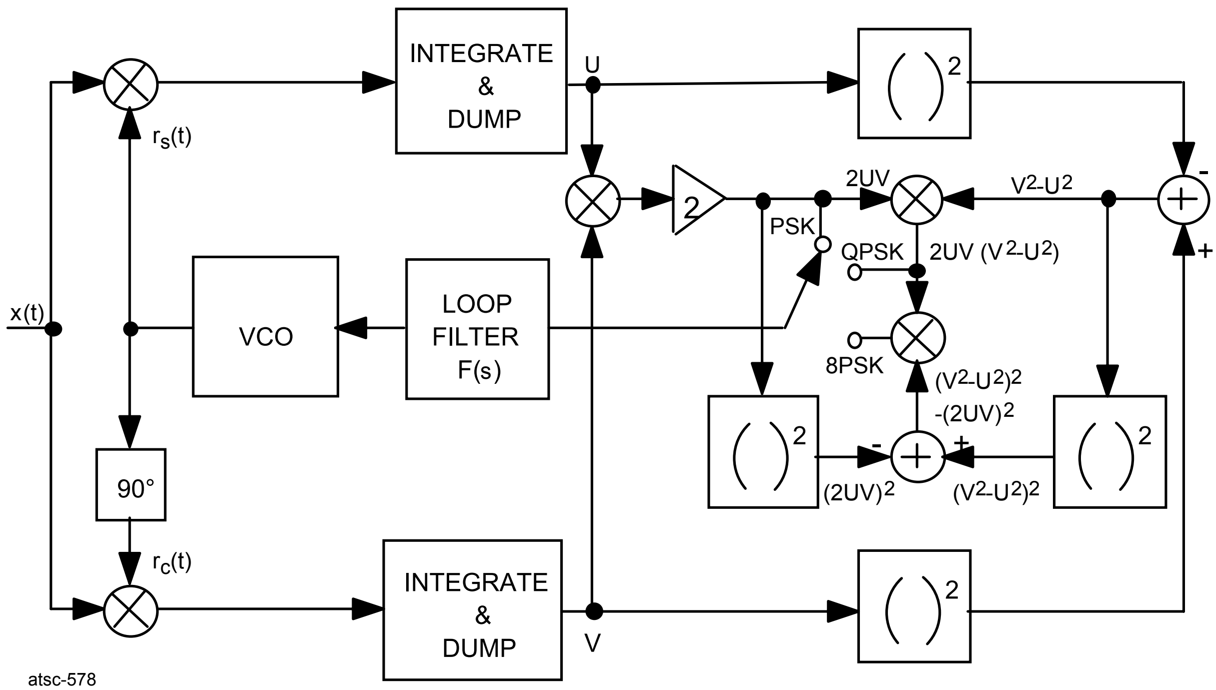


Figure 2.1-4: ARX II Receiver Modifications

2.2 MSK, GMSK, AND FQPSK-B MODULATION SIMULATIONS

Even as modified, the ARX II receiver can not accommodate Continuous Phase Modulation (MSK and GMSK) nor the new Feher QPSK (FQPSK) modulation. Because preliminary studies showed these modulation methods to be very bandwidth-efficient, it was important that they be included in Phase 3 of the *Efficient Modulation Methods Study*.

Phase 3 studies of MSK, GMSK, and FQPSK-B were accomplished assuming an ideal modulator and receiver. The ESA power amplifier described in Section 2.1.4 was used and both system losses and spectra are computed with this non-linear element. However, losses due to modulator non-linearities and imperfect carrier tracking and symbol synchronization are not included.

3.0 SIMULATION RESULTS

A principal Phase 3 study objective was the identification of modulation types having minimal RF spectrum width, reasonable end-to-end losses, and maximum interference immunity. Space missions have differing goals resulting in differing constraints and requirements. CCSDS Subpanel 1E has long suspected that there is not one *best* modulation type for all missions. Rather, there is likely to be a *preferred* modulation type for *each* mission type.

The key is to establish a set of mission categories into which missions having similar characteristics can be assigned. Each category can be examined to determine the best one or two modulation methods for that set. Clearly, the number of separate categories should be the minimum possible. Mission categories and recommended modulation methods are more fully examined in Section 4.3.

This Section contains the results of the Phase 3 *Efficient Modulation Methods Study* conducted at JPL. Following establishment of a *Reference Case*, each modulation method is compared. First, the baseband filter's bandwidth is selected using Bit-Error-Rate (BER) performance curves representing the end-to-end system performance. Second, RF spectra, generated using the selected baseband filter, are examined to find bandwidth efficiency and unwanted emissions. Finally, power containment curves are provided to find the *occupied bandwidth* and to easily compare relative bandwidth efficiencies.

3.1 REFERENCE MODULATION

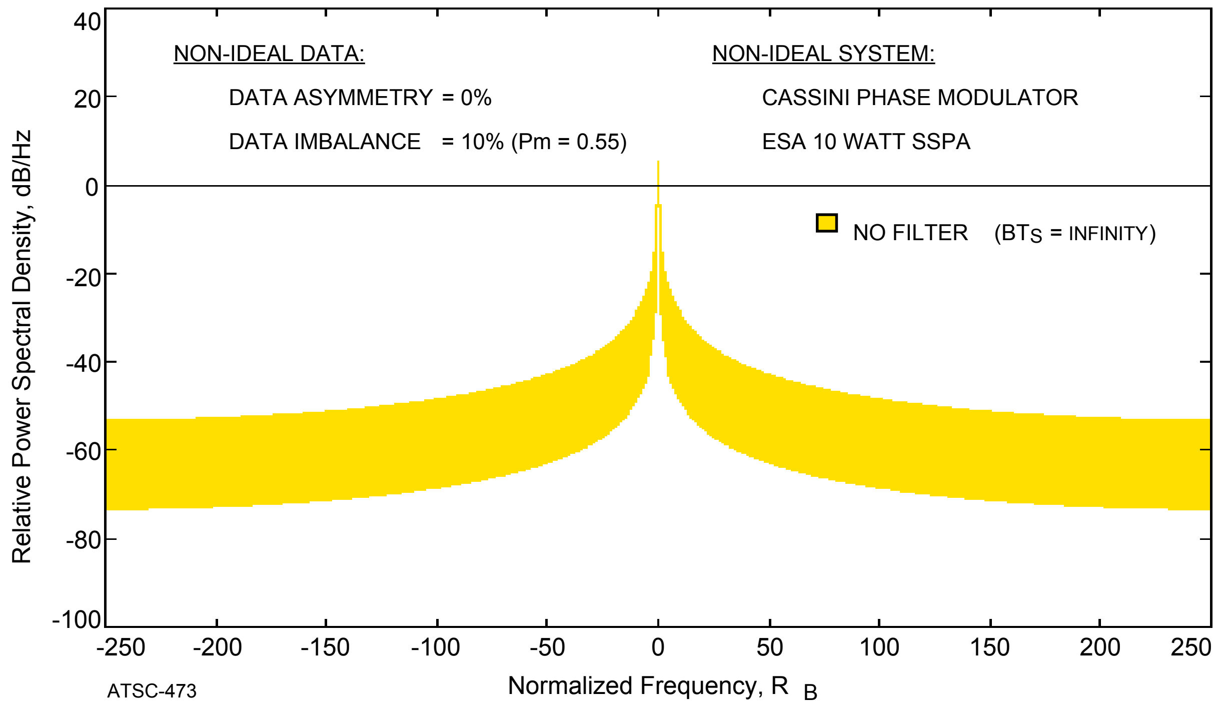
Determination of bandwidth efficiency requires a comparative reference. In the Phase 2 study, PCM/PM/NRZ was used because it is a residual carrier modulation providing a compact RF spectrum. However, PCM/PM/NRZ modulation suffers from certain disadvantages discussed below and its selection was always controversial. Therefore, the generally accepted BPSK/NRZ was adopted as the reference modulation type for this Phase 3 study.

All spectrum plots in Section 3 have a resolution bandwidth of 1.33 Hz. Figure 3.1-1 shows unfiltered BPSK/NRZ spectra using a Cassini modulator and non-ideal data. Figure 3.1-1a incorporates a 10% data imbalance (difference in +1s and -1s) and Figure 3.1-1b adds a 2% data asymmetry (duration of +1 compared to duration of -1) to the 10% data imbalance. Data asymmetry produces spikes substantially increasing the spectrum's width. Spectra are plotted over a frequency interval, $f_C \pm 250\ R_B$, making amplitudes beyond this span indeterminate. Table 3.1-1 summarizes the reference case measurements.

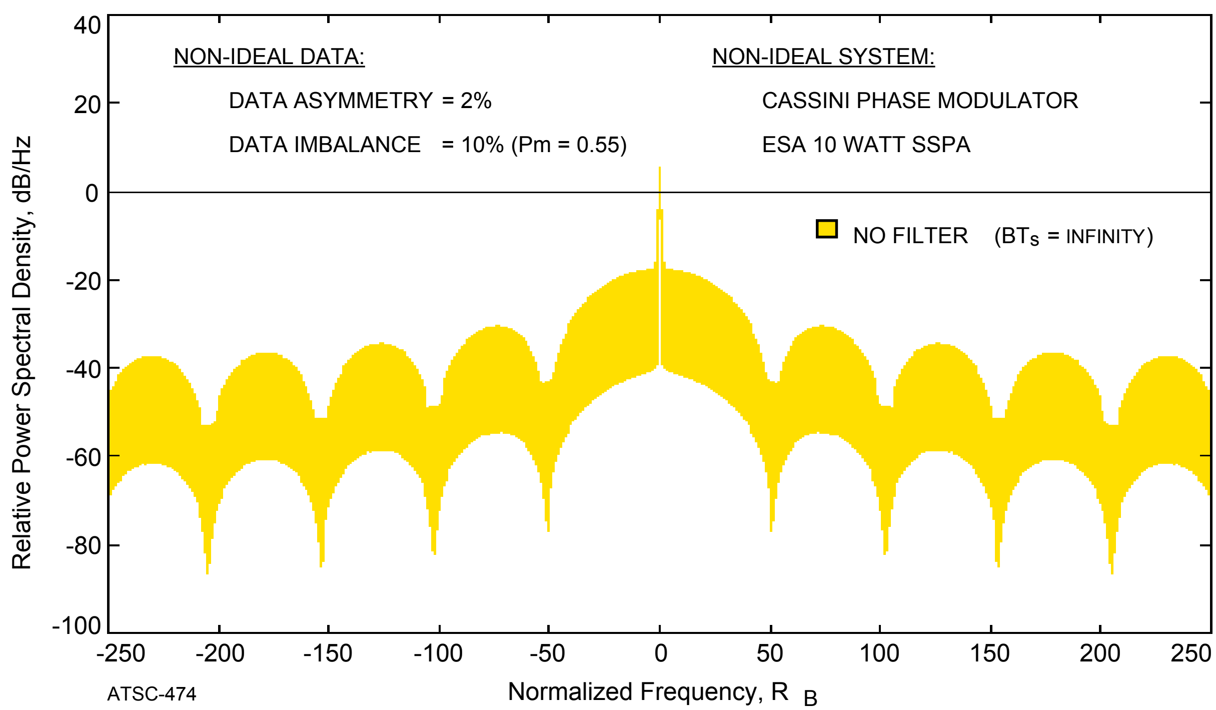
Figure 3.1-1 and Table 3.1-1 clearly demonstrate that unfiltered digital data transmission methods are unacceptable, particularly where there is data asymmetry. Data asymmetry (Figure 3.1-1b) introduces spikes into the RF spectrum at multiple $\pm R_B$ intervals increasing the level of *Unwanted Emissions* by 15-18 dB. Nulls in the discrete spectrum occur at:

$$R_B / 0 = R_B / 0.02 = 50\ R_B$$

where: 0 = data asymmetry



3.1-1a: 10% Data Imbalance and No Data Asymmetry



3.1-1b: 10% Data Imbalance and 2% Data Asymmetry

Figure 3.1-1: Unfiltered BPSK/NRZ Reference Modulation Spectra with Non-Ideal Data

Table 3.1-1: Summary of Reference Modulation Measurements

Data Imbalance Only (Figure 3-1a)		Data Imbalance and Asymmetry (Figure 3-1b)	
dB Below Sideband Peak	Spectrum Width R_B	dB Below Sideband Peak	Spectrum Width R_B
-20	± 3.6 R_B	-20	± 19.1 R_B
-30	± 11.6 R_B	-30	± 40.1 R_B
-40	± 74.8 R_B	-40	> ± 250 R_B
-50	± 130.5 R_B	-50	> ± 250 R_B
-60	>> ± 250 R_B	-60	>> ± 250 R_B

All modulation methods discussed below, are measured with respect to the unfiltered BPSK/NRZ reference case and the results are summarized in Table 4.1-2. Additionally, each modulation type also includes an unfiltered (i.e., $BT_S = 4$) spectrum on the same figure for reference purposes. Note: Unfiltered spectra, found on the figures for each modulation method, is for the same modulation method under discussion and not the BPSK/NRZ reference case.

Because the *Universal Phase Modulator's* sample-and-hold and baseband filter substantially remove all data asymmetry, comparisons to BPSK/NRZ are made with Figure 3-1a (i.e., 0 = 0). This represents a *worst case* since spectra with spikes due to filtering are being compared to spectra without spikes resulting from data asymmetry.

All spectrum plots and bandwidth measurements are stated in terms of R_B. This normalized parameter is described in Section 2.1 (equation 2-1) and represents the frequency span occupied by one sidelobe of the modulating signal. Readers can easily convert Section 3 measurements to their desired data rate by multiplying their data rate by the value of R_B.

For example, sidebands of unfiltered BPSK/NRZ modulation, with a 10% data imbalance and a 2% data asymmetry, are 20 dB below the peak at ± 19.1 R_B (Table 3.1-1). If the modulating data rate is 10 ks/s, then the sidebands will be 20 dB below the peak amplitude at ± 191 kHz away from the center frequency.

All spectra are plotted using a resolution bandwidth of 1.33 Hz. This was the narrowest feasible simulation bandwidth using SPW. It is sufficiently close to 1 Hz so that the continuous and discrete portions of spectra are depicted with the proper relationship to one another. Readers can easily adapt these separate parts of the spectrum for any desired bandwidth by adjusting the continuous portion by the ratio of the new bandwidth to 1 Hz.

3.2 PCM / PM / NRZ MODULATION

Phase modulation techniques are subdivided into two categories: residual carrier and suppressed carrier. The distinction lies in the presence (residual) or absence (suppressed) of an RF carrier component. Traditionally, space agencies employed the former. However, as data rates have increased and Power Flux Density (PFD) became a problem for Earth orbiting spacecraft, many mission designers began using suppressed carrier modulation. For this Phase 3 study, the residual carrier modulation index was 1.2 radians (peak).

Nevertheless, residual carrier systems are still widely used, particularly where simultaneous telemetry and ranging data capture is required. Unbalanced QPSK (UQPSK) is occasionally used in suppressed carrier applications requiring simultaneous telemetry and ranging. However, absent a low rate data type or a realtime reallocation of power, the UQPSK quadrature channel may not be used effectively when ranging is turned off.

Although care must be taken to control data imbalance, PCM/PM/NRZ modulation provides the narrowest RF spectrum of the residual carrier types tested. High levels of data imbalance can result in large end-to-end system losses making this modulation type unsuitable in applications having low telemetry performance margins. Generally, convolutional encoding ensures a sufficient symbol transition density to keep losses at an acceptable level.

PCM/PM/NRZ modulation has been used successfully on NASA’s Polar spacecraft and is under consideration for some future missions. Where a remnant carrier is required and convolutional coding is employed, this modulation type deserves serious consideration.

3.2.1 PCM / PM / NRZ Modulation Bit-Error-Rate (BER)

End-to-end system performance measurements were a principal Phase 3 study objective. The best, most compact, RF spectrum is of little value if the Earth station’s receiver cannot capture the telemetry signal. BER vs E_B / N_0 plots were created for Butterworth, Bessel, and Square Root Raised Cosine (SRRC) filters. Curves representing Symbol Bandwidth C Time (BT_S) values of 1, 2, and 3 were plotted for the two passive (Butterworth and Bessel) filter types. BER vs E_B / N_0 plots for SRRC filters included a single value " = 1 curve.

Figure 3.2-1 contains plots for the three filter types. Inspecting these curves at BER = 1 x 10^{-3}, shows BT_S values of 2 and 3 to be almost identical. Conversely, losses for BT_S = 1 are greater increasing the required E_B / N_0. Applying the criteria set forth in Section 1.5.2, a value of BT_S = 2 was selected for Butterworth and Bessel filters. Note that loss increases from BT_S = 4 to BT_S = 2 or 3 are insignificant. System losses and its components are summarized in Table 4.1-1.

System losses can be found by subtracting the E_B / N_0 value for Ideal PCM/PM/NRZ from the corresponding E_B / N_0 value for a BT_S = 2 or 3 at a BER = 1 x 10^{-3}. Each plot also contains an ideal BPSK/NRZ modulation curve for reference purposes. To a first order, system losses for all three filter types appear to be about the same. Thus, the selection of the best filter depends upon its complexity and the resulting spectrum.

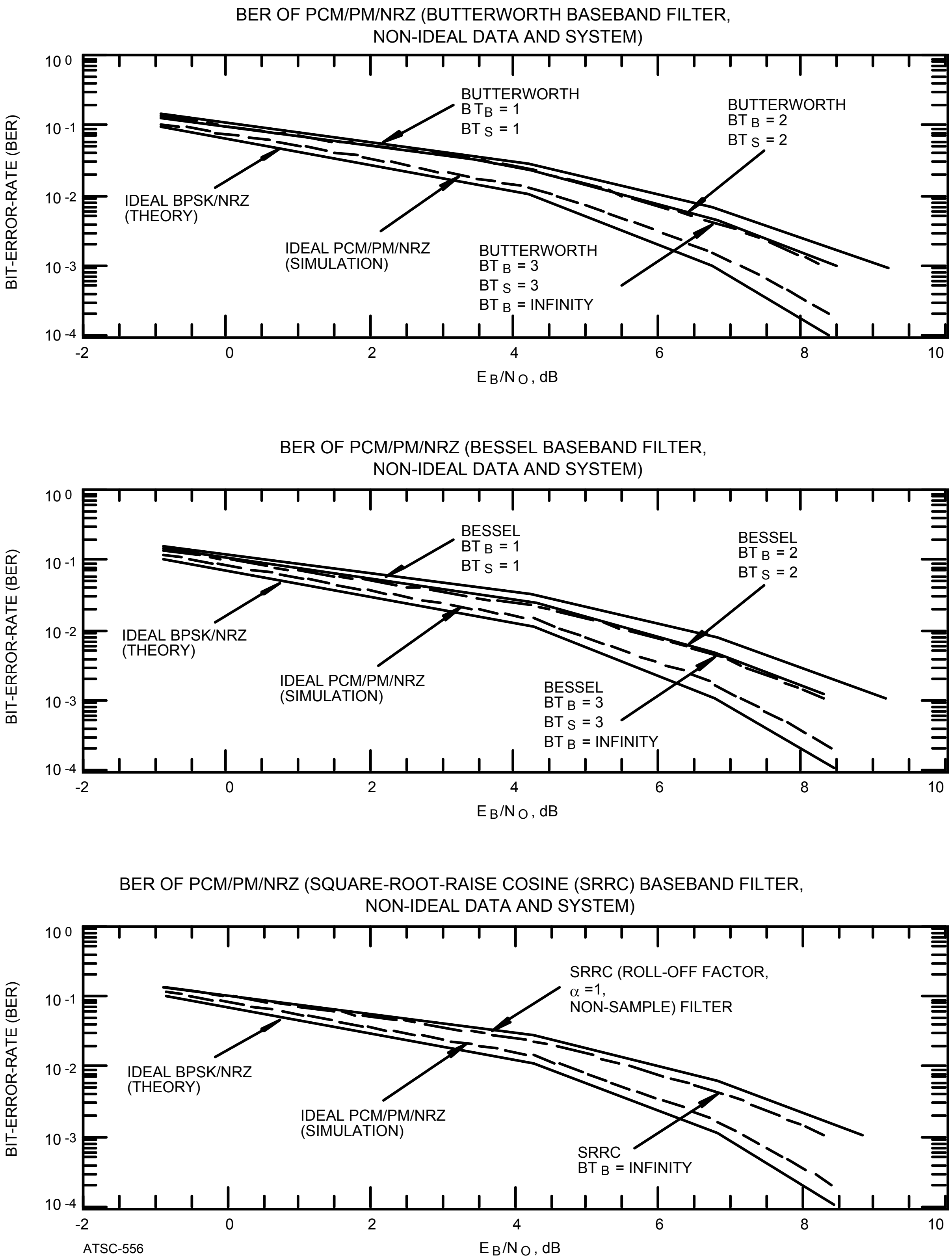


Figure 3.2-1: PCM/PM/NRZ Modulation Bit-Error-Rate

3.2.2 PCM / PM / NRZ Modulation Spectra

Figure 3.2-2 shows PCM/PM/NRZ spectra, measured at the SSPA's output, for span bandwidths of 20 R_B (Fine Detail) and 500 R_B (Broadband Spectra). Four filter cases appear for each of the modulation types evaluated in Phase 3 representing an unfiltered reference and three baseband filtered cases. The topmost, yellow (or light grey) curve always represents the unfiltered (i.e., $BT_S = 4$) case of the modulation type under evaluation. It is placed there for comparative purposes.

Because 0 = 0 for the unfiltered case, no spikes appear in the spectrum. However, filtering introduces RF spectrum spikes at R_B intervals (Figure 3.2-2a). Note that the amplitude of the spikes drops below that for the unfiltered spectrum at ± 7 R_B, ± 6 R_B, and ± 3 R_B for the Bessel, Butterworth, and Square Root Raised Cosine filtered cases respectively. The net result of baseband filtering is to widen the spectrum close to the center frequency while significantly restricting its width at larger values of R_B. This effect is clearly evident in Figure 3.2-2b.

Figure 3.2-2b also demonstrates that Butterworth and Square Root Raised Cosine baseband filters are considerably more effective in restricting the RF spectrum's width than is a Bessel baseband filter. Because of its simplicity, the Butterworth filter ($BT_S = 2$) appears to be the best choice for baseband filtering.

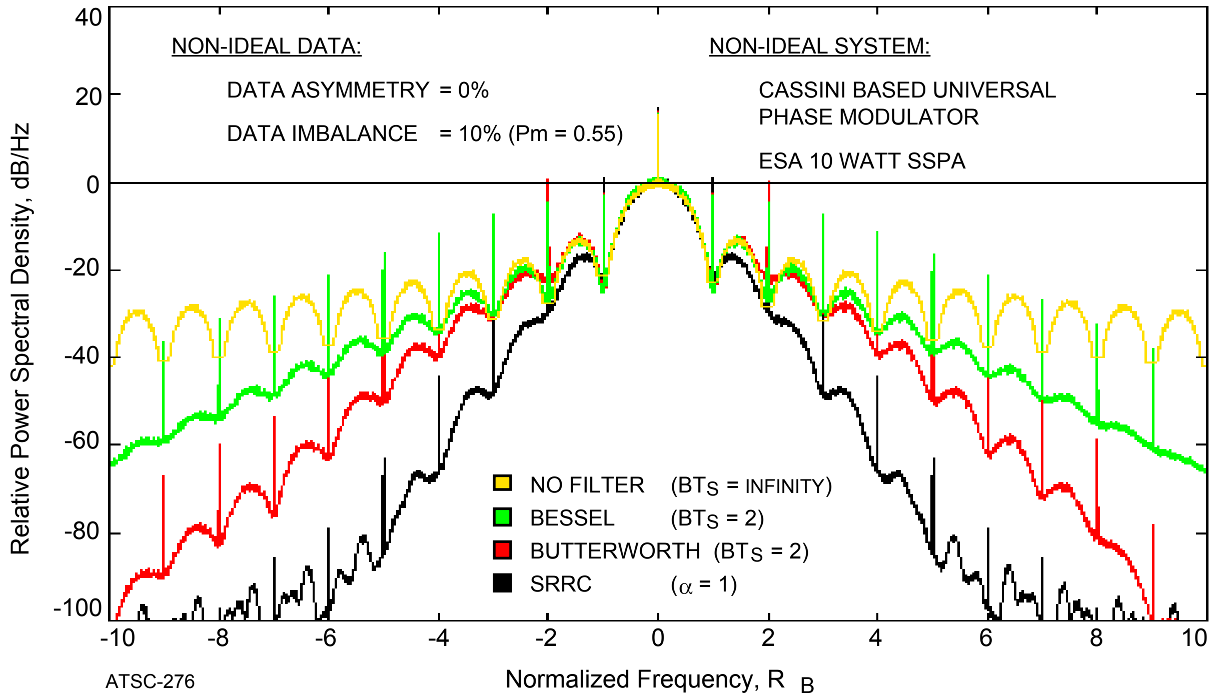
3.2.3 PCM / PM / NRZ Modulation Power Containment

Figure 3.2-3 depicts the one-sided bandwidth of a PCM/PM/NRZ signal. Modulation on an RF carrier doubles the one-sided bandwidth. Using a Butterworth $BT_S = 2$ filter, the *occupied bandwidth* is about ± 2 R_B (4 R_B total spectrum width).

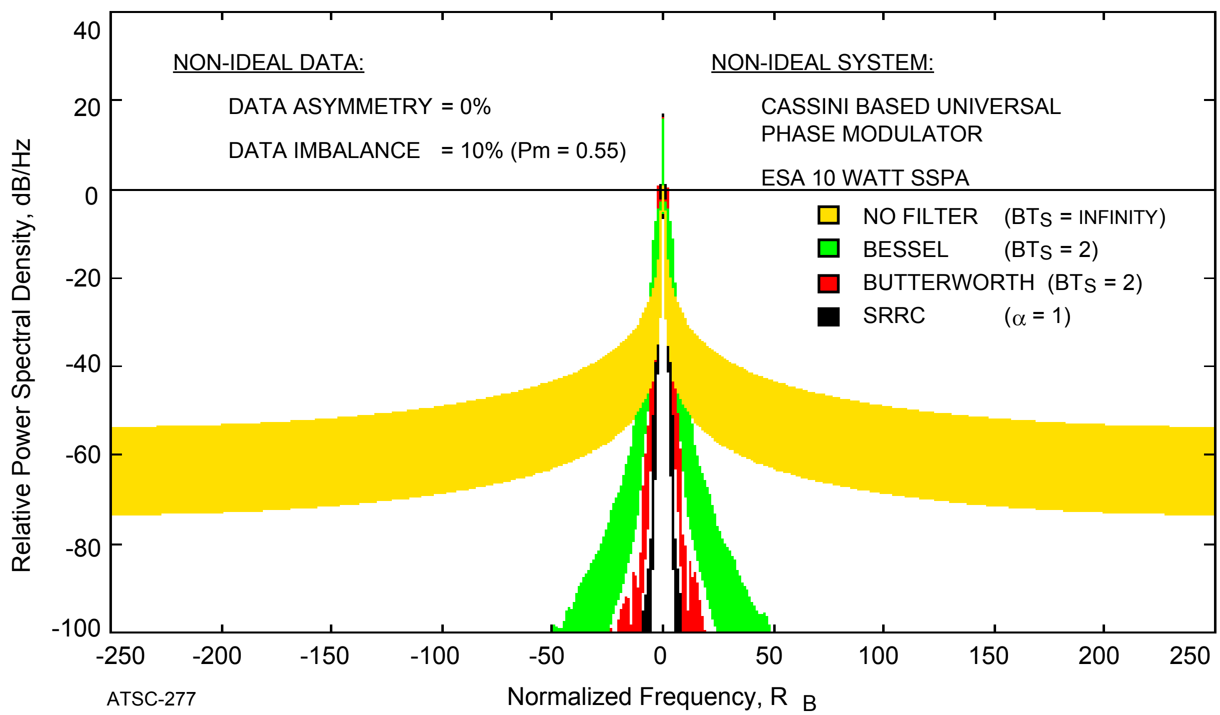
Table 4.1-2 contains the two-sided bandwidth as measured using SPW. 8.2 R_B are needed to be 20 dB below the data sideband's peak amplitude. The 4 R_B difference between *occupied bandwidth* and the -20 dB point in Table 4.1-2 results from spikes due to baseband filtering. In Table 4.1-2, no spectral components exceed -20 dB beyond a bandwidth of 8.2 R_B. However, the power contained in the spikes is vanishingly small. Thus, for filtered phase modulated signals, the power containment bandwidth will be substantially smaller than that required for an equivalent sideband attenuation.

3.2.4 PCM / PM / NRZ Modulation Study Conclusions

PCM/PM/NRZ is the most bandwidth-efficient residual carrier modulation method investigated. It should receive serious consideration by projects having moderate data rate requirements (20 ks/s-2 Ms/s) <u>when a residual carrier is required</u>. Because system losses are very sensitive to data imbalance, some means for ensuring an approximately equal number of +1s and -1s over a time interval of $1/B_L$ must be provided (where B_L is the receiver phase-locked loop's bandwidth expressed in Hz). Convolutional encoding may be sufficient. If not, the CCSDS recommended data randomizer should be used.[6]



3.2-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.2-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.2-2: PCM/PM/NRZ Modulation Spectra

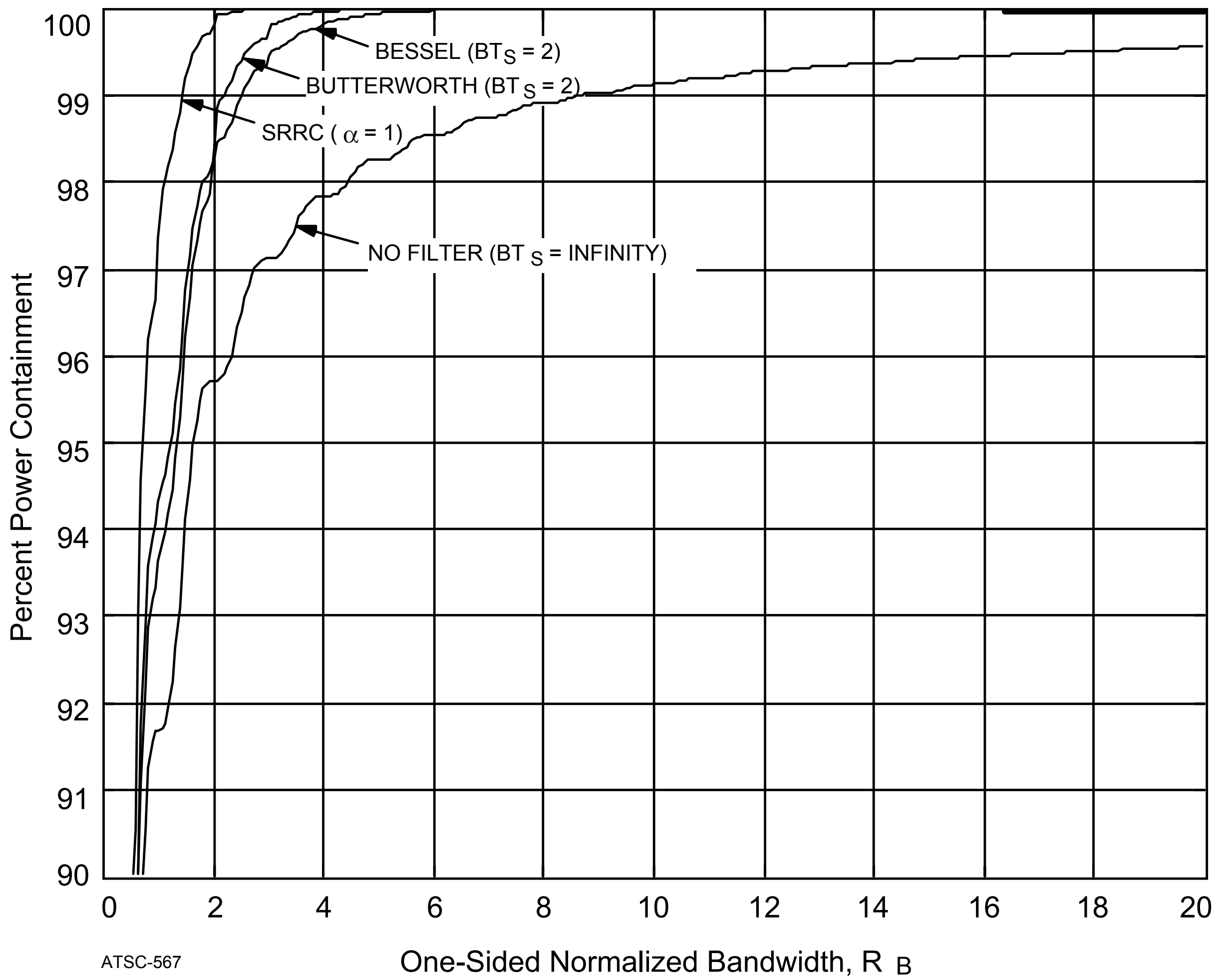


Figure 3.2-3: PCM/PM/NRZ Modulation Power Containment

Additionally, PCM/PM/NRZ modulation requires carrier distinguishability be maintained. Since the data sideband's spectrum peaks at the RF carrier frequency, the data rate must be sufficiently high to ensure that the data's power spectral density does not interfere with carrier detection. With a rate ½ convolutional encoding, a data rate of 10 kb/s may not be sufficient for some applications. At such a low symbol rate, the Earth station receiver phase-locked-loop's bandwidth will need to be quite narrow. For low data rate applications, where carrier distinguishability is not sufficient or where interference to the tracking loop may occur, UQPSK modulation may be preferred. Each mission's requirements should be analyzed to ensure proper operation where PCM/PM/NRZ is used.

3.3 PCM / PM / Bi-N MODULATION

Where residual carrier modulation must be used, Manchester encoding is frequently thought to be preferable to PCM/PM/NRZ modulation. This is so because there is a spectral null at the RF carrier frequency increasing its distinguishability. Additionally, data imbalances, which can pose problems for PCM/PM/NRZ modulation, are eliminated.

PCM/PM/Bi-N eliminates data imbalance by the modulo-2 addition of information data with a double-frequency squarewave. Each Manchester encoded information data bit comprises both a +1 and !1 with the result that the number of +1s and -1s are approximately equal over a time interval of $1/B_{LO}$ where B_{LO} is the receiver phase locked loop's bandwidth. However, spectral bandwidth is doubled.

3.3.1 PCM / PM / Bi-N Modulation Bit-Error-Rate (BER)

Figure 3.3-1 displays the BER vs E_B / N_0 plots for the three filter types using PCM/PM/Bi-N modulation. Comparing these curves with those for PCM/PM/NRZ modulation (Figure 3.2-1) reveals that losses for PCM/PM/Bi-N are significantly less than for PCM/PM/NRZ modulation. At a BER = 1 x 10^{-3} the difference in required E_B / N_0 is about 0.7 dB. Increased losses found with PCM/PM/NRZ result principally from the 10% *data imbalance* included in this study. However, the figure shows a distinct difference between the ideal curve and the reference BPSK/NRZ curve.

The double-frequency squarewave requires the baseband filter's bandwidth be reset. Loss measurements in Phase 2 showed that a BT_S = 2 provided the best compromise between system losses and RF spectrum width for PCM/PM/NRZ modulation. With PCM/PM/Bi-N modulation, a BT_S = 2 filter bandwidth is retained; however, it is based on the Manchester code's symbol period (BT_S), rather than on BT_B, the information data bit's period. Such a filter would be equivalent to a BT_B = 4 for the information data. System losses and its components are summarized in Table 4.1-1

3.3.2 PCM / PM / Bi-N Modulation Spectra

While PCM/PM/Bi-N improves RF carrier detectability over PCM/PM/NRZ modulation, the bandwidth efficiency is substantially reduced. Comparing Figures 3.2-2b and 3.3-2b, for PCM/PM/NRZ and PCM/PM/Bi-N modulations respectively, shows that the !100 dB level is reached at ± 50 R_B for the former while ± 100 R_B are required for the latter. One concerned with spectrum efficiency should avoid the use of PCM/PM/Bi-N whenever possible.

As in the PCM/PM/NRZ case, filtered spectra are actually wider than the unfiltered spectra in the neighborhood of the RF carrier frequency. However by ± 12 R_B filtered spectra become narrower and remain so thereafter. Filtering substantially improves the bandwidth efficiency as the distance from the RF carrier is increased.

For this study, timing errors between the information data bits and Manchester code symbols were considered negligible. Nevertheless, additional spikes are introduced into the RF spectrum from the 10% data imbalance. With PCM/PM/NRZ modulation, spikes occurred only in the nulls at ± R_B intervals. For PCM/PM/Bi-N modulation, spikes can be seen in both the nulls and at the peaks of the spectrum (Figure 3.3-2a). *Note: These spikes are present when O = 0. Spikes due phase domain filtering appear at spectrum nulls while spikes resulting from data imbalance appear at the peaks.*[7] Since some data imbalance is always likely to be present, this finding suggests that PCM/PM/Bi-N modulation users may have been operating with spectral spikes all along.

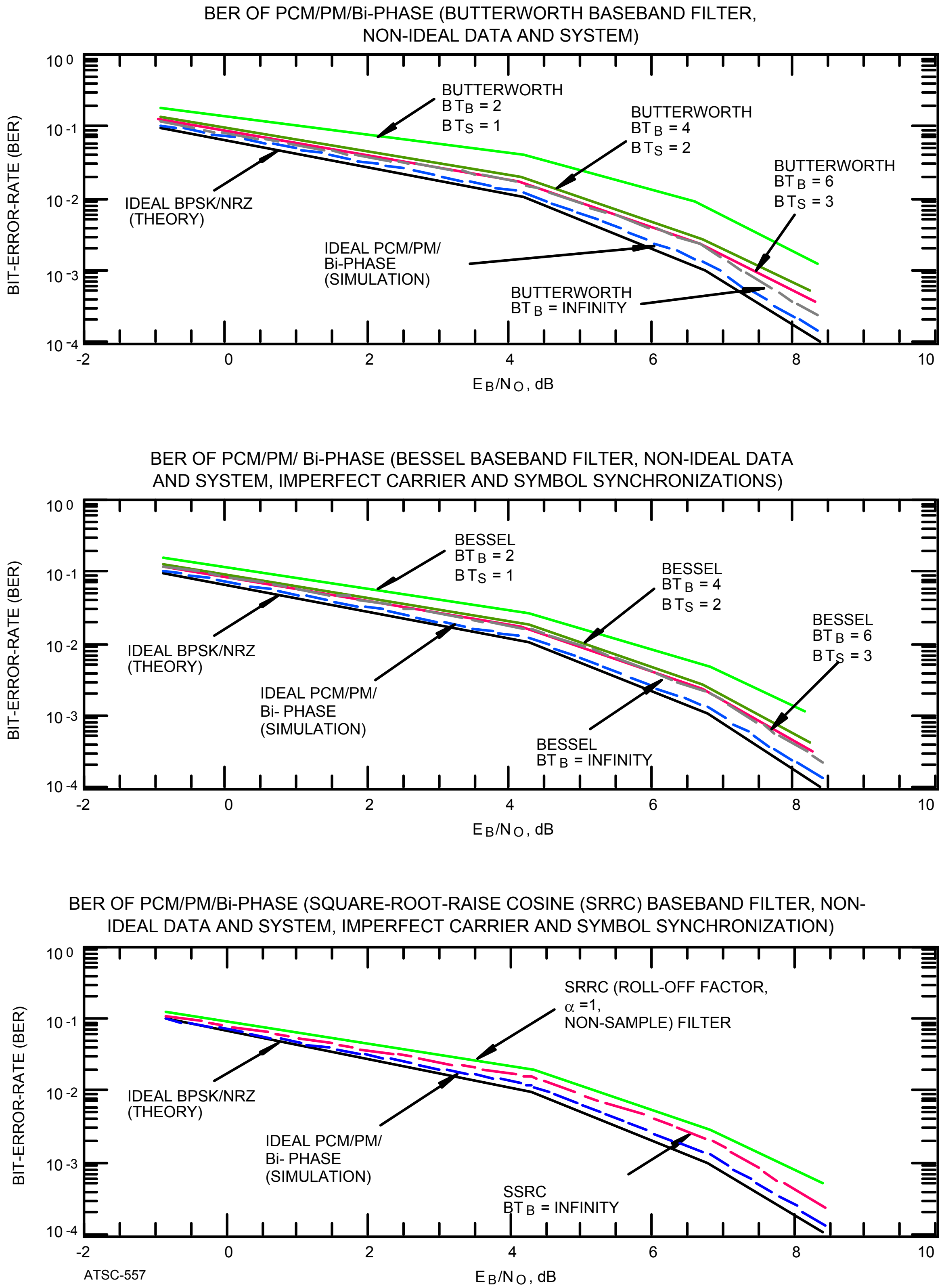
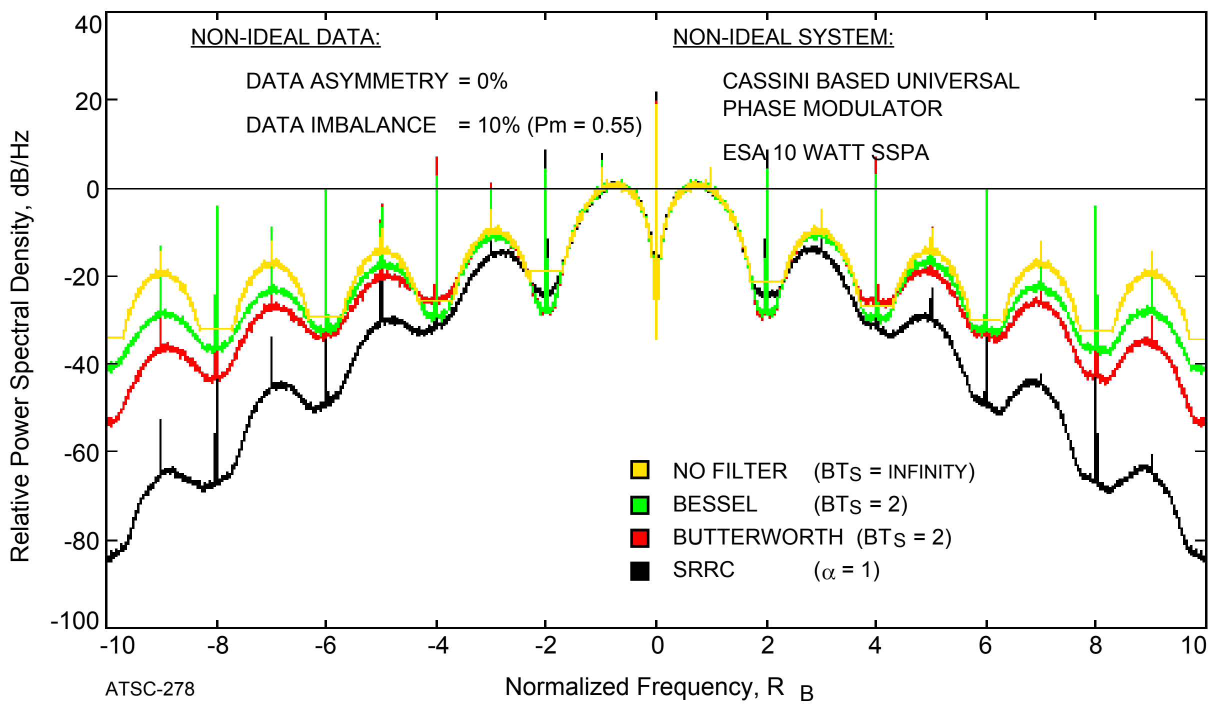
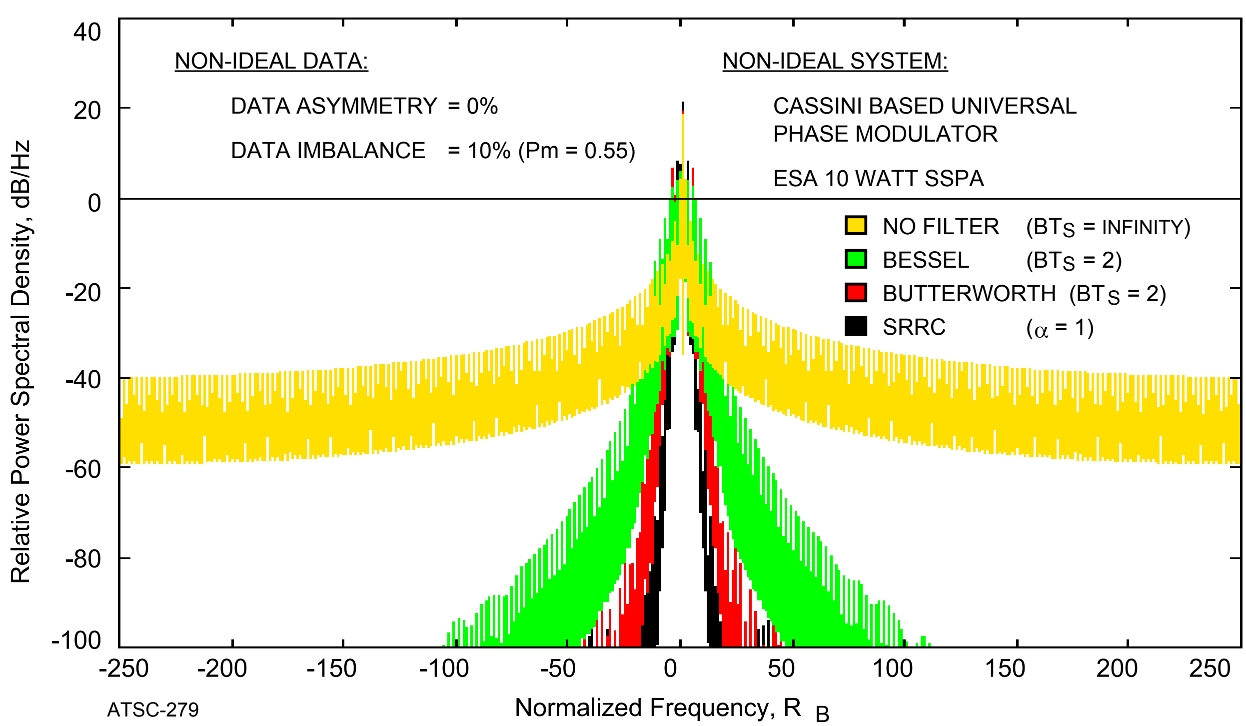


Figure 3.3-1: PCM/PM/B-N Bit-Error-Rate



3.3-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.3-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.3-2: PCM/PM/Bi-N Modulation Spectra

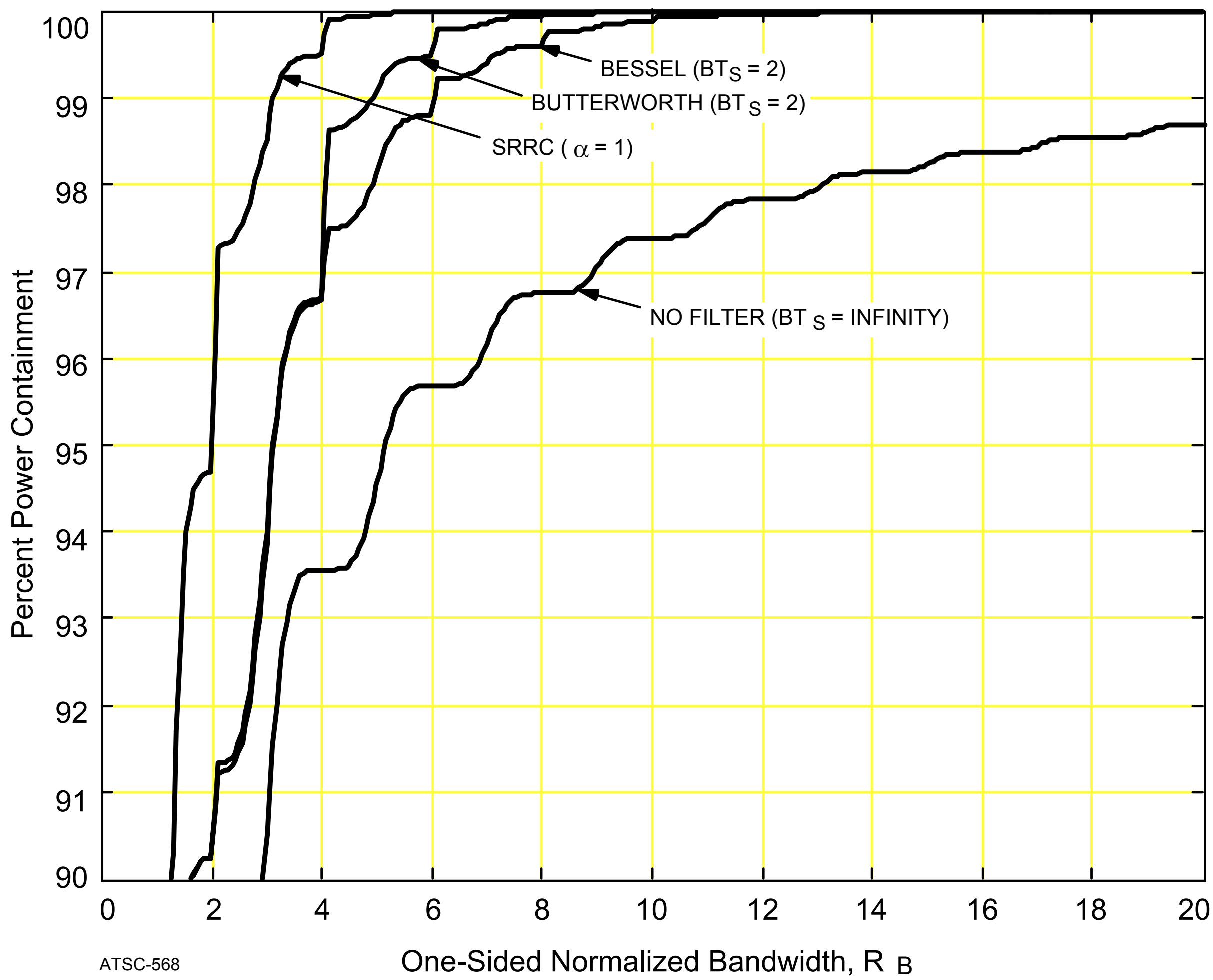


Figure 3.3-3: PCM/PM/Bi-N Modulation Power Containment

Some *scalloping* is discernable in the darker portion of Figure 3.3-2b. It appears to be periodic at approximately 10 R_B. Concern was expressed that this may be a result of the Manchester encoding process. To resolve the matter, the original SPW data was expanded in a series of steps so that individual spectral lobes, and spikes, became identifiable. No evidence of a periodic signal was found. The authors have concluded that these variations are an artifact of the graphics presentation process and are not actually present in the RF spectrum.

3.3.3 PCM / PM / Bi-N Modulation Power Containment

As expected, Figure 3.3-3 shows that power containment for PCM/PM/Bi-N modulation is twice that of PCM/PM/NRZ. Here the *occupied bandwidth* is approximately 9 R_B using a Butterworth, BT_S = 2 filter. PCM/PM/Bi-N modulation was found to be one of the *least* bandwidth-efficient modulation types considered in the Phase 3 study.

3.3.4 PCM / PM / Bi-N Modulation Study Conclusions

If a residual carrier is required and either the data imbalance is greater than 5% ($-_{M}$ or $-_{S} \$ 0.525$) or the data's symbol rate is so low that RF carrier distinguishability may be impaired, PCM/PM/NRZ may be unsuitable. In such cases, PCM/PM/Bi-N modulation could be considered. RF spectrum efficiency is reduced by half as compared to PCM/PM/NRZ making PCM/PM/Bi-N modulation the least bandwidth-efficient type in this study.

Space agency Spectrum Managers truly concerned about bandwidth efficiency should encourage the use of modulation methods other than PCM/PM/Bi-N, particularly at data rates above 1 Mb/s. Specifically, the need for a residual carrier should be reviewed to ensure that it is absolutely necessary. If not, BPSK, UQPSK, or QPSK modulation should be considered.

3.4 BPSK / NRZ MODULATION

BPSK/NRZ modulation is typically used as a reference for other modulation methods for comparing bandwidth efficiency, Bit-Error-Rate (BER) performance, and system losses. Unlike PCM/PM/NRZ, BPSK/NRZ modulation does not exhibit large system losses at high levels of data imbalance obviating the need for Manchester encoding. Nevertheless, problems can arise in the symbol synchronizer's Digital Transition Tracking Loop (DTTL) at low symbol transition densities where it may experience difficulty in remaining locked. Since symbol synchronizers are commonly implemented using DTTLs, the spacecraft must provide an adequate symbol transition density.

BPSK/NRZ modulation is useful if the symbol transition density is sufficient for the DTTL. Generally, convolutional encoding provides an adequate data transition density. In these cases, it is preferred over Manchester encoded BPSK because of the substantially narrower bandwidth.

3.4.1 BPSK / NRZ Modulation Bit-Error-Rate (BER)

Bit-Error-Rate (BER) plots for the three filter types can be found in Figure 3.4-1. These plots are similar to those for PCM/PM/Bi-N modulation and the E_B / N_0 required for a 1 x 10^{-3} BER, with a Butterworth (BT_S = 2) filter, is within 0.1 - 0.2 dB. System performance differences are so small that BER cannot be used to discriminate between these two modulation types. System losses and its components are summarized in Table 4.1-1.

3.4.2 BPSK / NRZ Modulation Spectra

Figure 3.4-2 shows the RF spectra for this modulation type. Except for the lack of an RF carrier component, these spectra are virtually indistinguishable from those for PCM/PM/NRZ. This is so for both the filtered and unfiltered cases. The apparent RF carrier component, extending above the 0 dB reference line, is actually a dc component introduced by the 10% data imbalance.

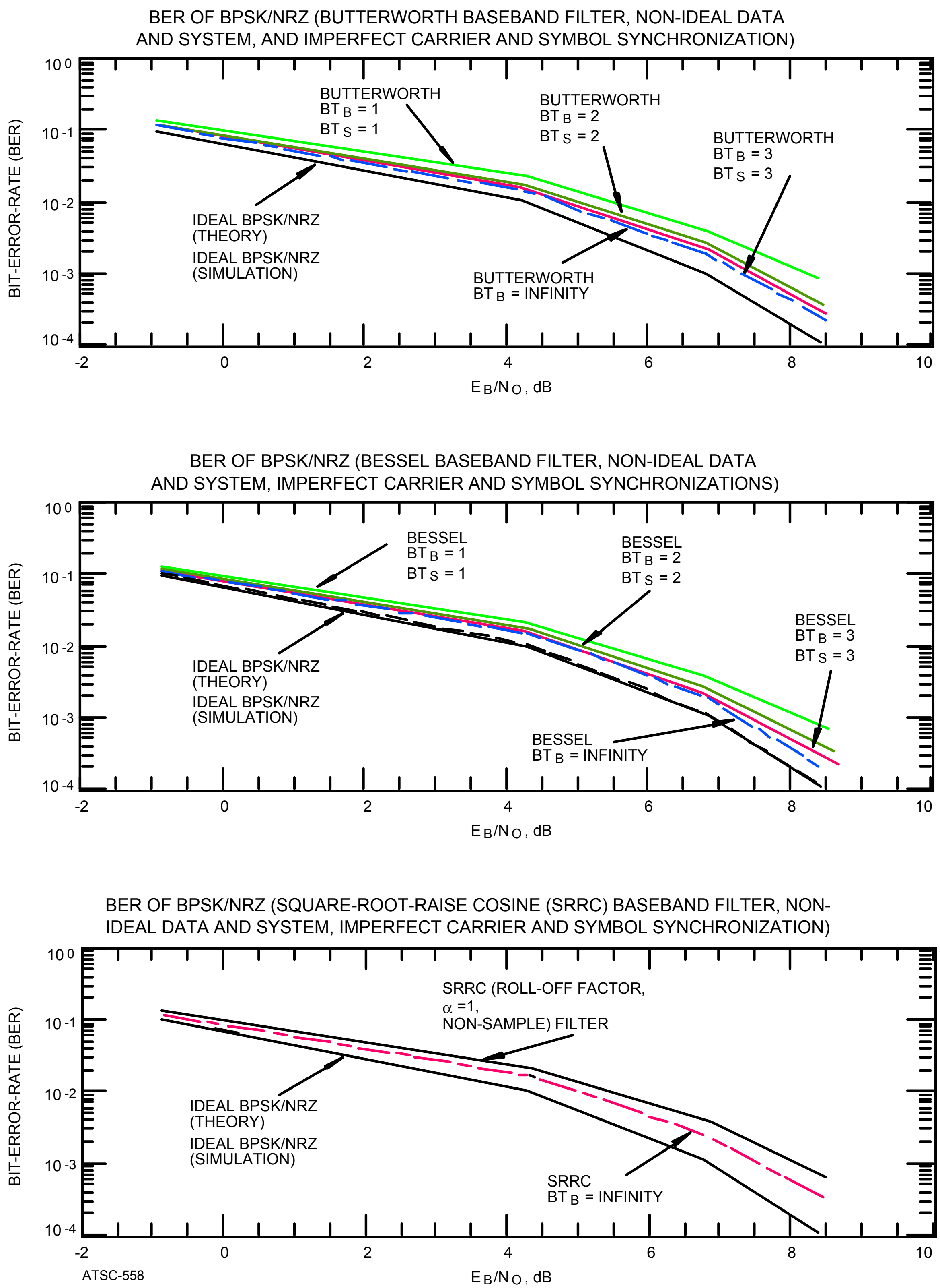
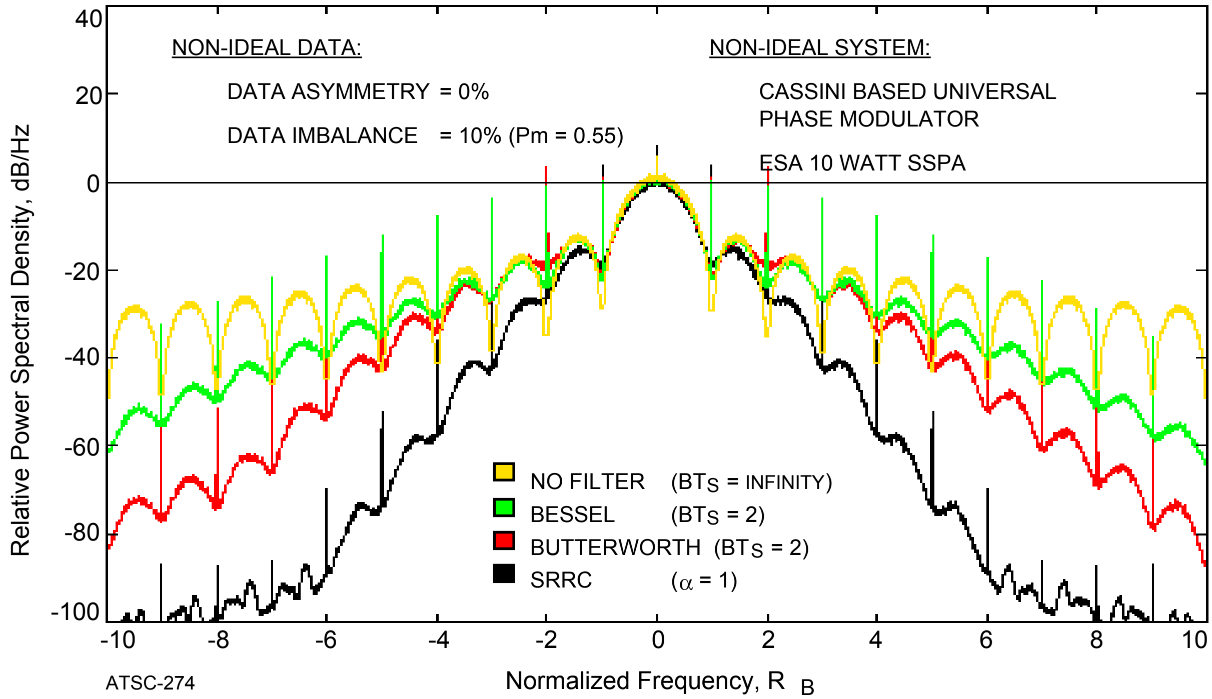
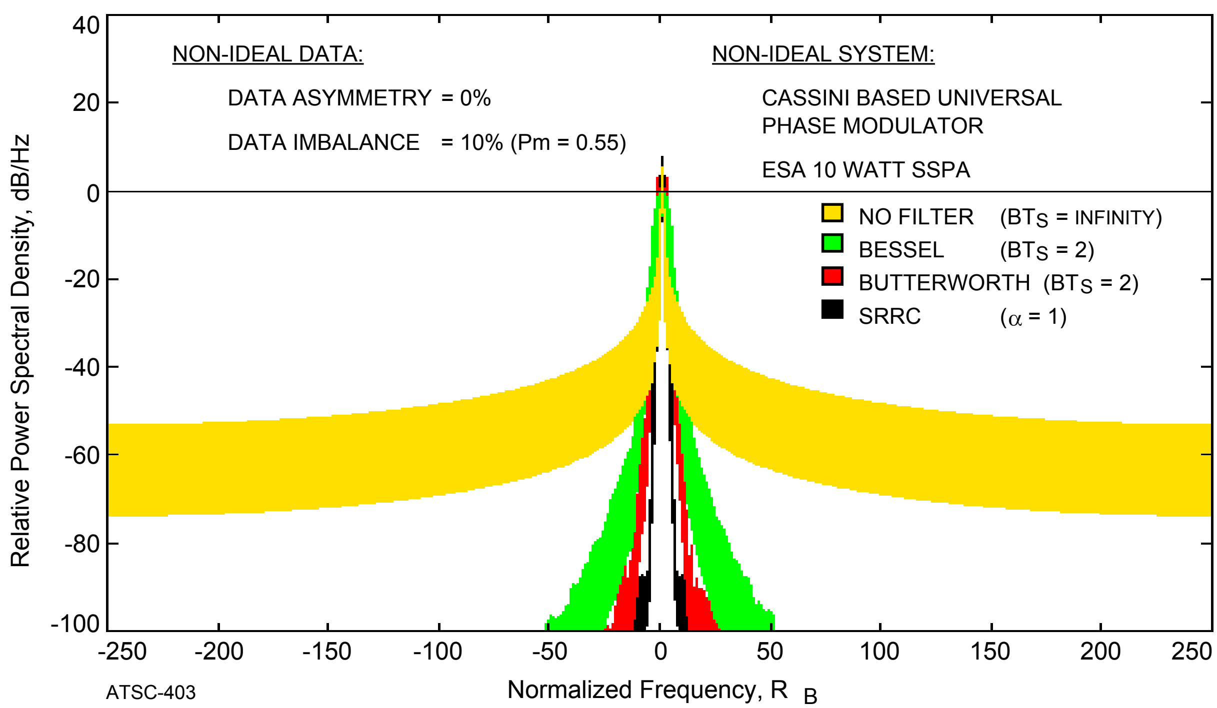


Figure 3.4-1: BPSK/NRZ Modulation Bit-Error-Rate



3.4-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.4-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.4-2: BPSK/NRZ Modulation Spectra

Comparing filtered BPSK/NRZ and PCM/PM/NRZ spectra (Figures 3.4-2 and 3.2-2), the former appears to be slightly wider than the latter. This is the result of placing all transmitted power in the BPSK/NRZ modulation sideband. PCM/PM/NRZ modulation does retain a portion of the total power for the residual carrier component lowering the modulation sideband power. To a first order, Figures 3.2-2 and 3.4-2 demonstrate that BPSK/NRZ modulation has no RF bandwidth advantage over PCM/PM/NRZ modulation.

Conversely, BPSK/NRZ has a clear spectral advantage over the PCM/PM/Bi-N modulation (Figure 3.3-2). Absent a high data imbalance level causing symbol synchronization problems, BPSK/NRZ appears to offer the best compromise between system losses and spectral efficiency of the modulation methods considered thus far.

3.4.3 BPSK / NRZ Modulation Power Containment

Figure 3.4-3 profiles BPSK/NRZ modulation power containment. Comparing with Figure 3.2-3, BPSK/NRZ can be seen to have an *occupied bandwidth* roughly 50% greater than that of PCM/PM/NRZ, using a 1.2 radian (peak) modulation index, (6 R_B vs 4 R_B). Nevertheless, BPSK/NRZ is reasonably bandwidth-efficient and deserves consideration for some applications.

3.4.4 BPSK / NRZ Modulation Study Conclusions

Missions not requiring a residual carrier and having modest data rates (20 ks/s - 200 ks/s) should consider BPSK/NRZ modulation first. It provides a good compromise between spectrum efficiency and simplicity of design.

While data imbalance does not result in system losses as in the case of PCM/PM/NRZ modulation, the statistics of each application should be reviewed. Agencies employing a DTTL architecture in their symbol synchronizers, must ensure a sufficient transition density to acquire and maintain synchronization. Manchester encoding prior to BPSK modulation can ensure sufficient transitions. As with PCM/PM/Bi-N modulation, there is a 100% penalty in spectrum efficiency over the NRZ equivalent.

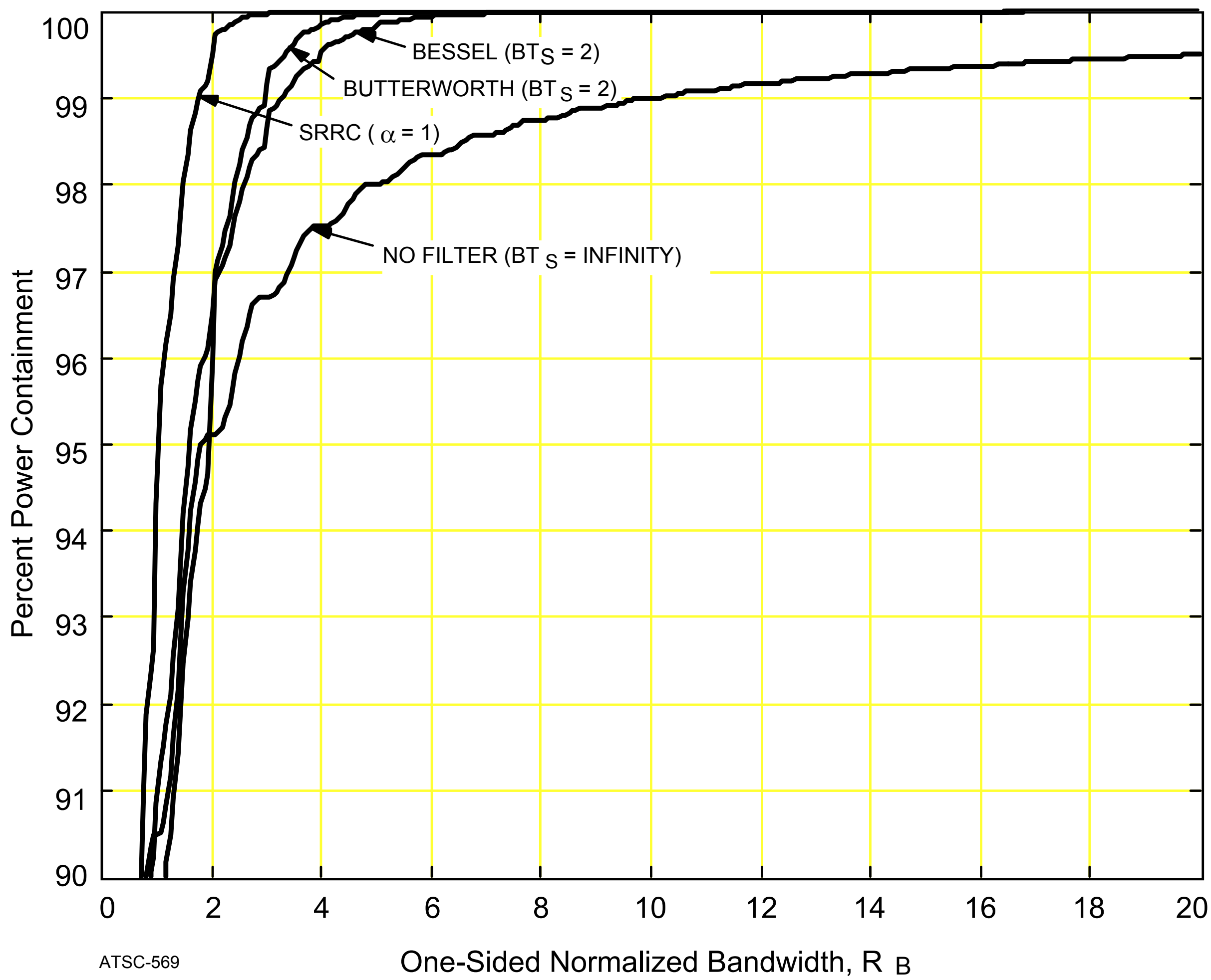


Figure 3.4-3: BPSK/NRZ Modulation Power Containment

3.5 BPSK / Bi-N MODULATION

This modulation method is useful where the modulating symbol transition density, due to data imbalance, is so low that the DTTL in the symbol synchronizer may lose lock. Its application is likely to be limited because most telemetry links are convolutionally encoded.

3.5.1 BPSK / Bi-N Modulation Bit-Error-Rate (BER)

Figure 3.5-1 provides BER performance for BPSK/Bi-N modulation. With a Butterworth $BT_S = 2$ filter, its performance is similar to, but slightly poorer than, PCM/PM/Bi-N and BPSK/NRZ modulations. BER behavior of BPSK/Bi-N is certainly better than that of PCM/PM/NRZ (Figure 3.2-1). Of course, the 10% data imbalance adversely affected the losses of PCM/PM/NRZ which was not the case with the PCM/PM/Bi-N or BPSK/Bi-N modulation types.

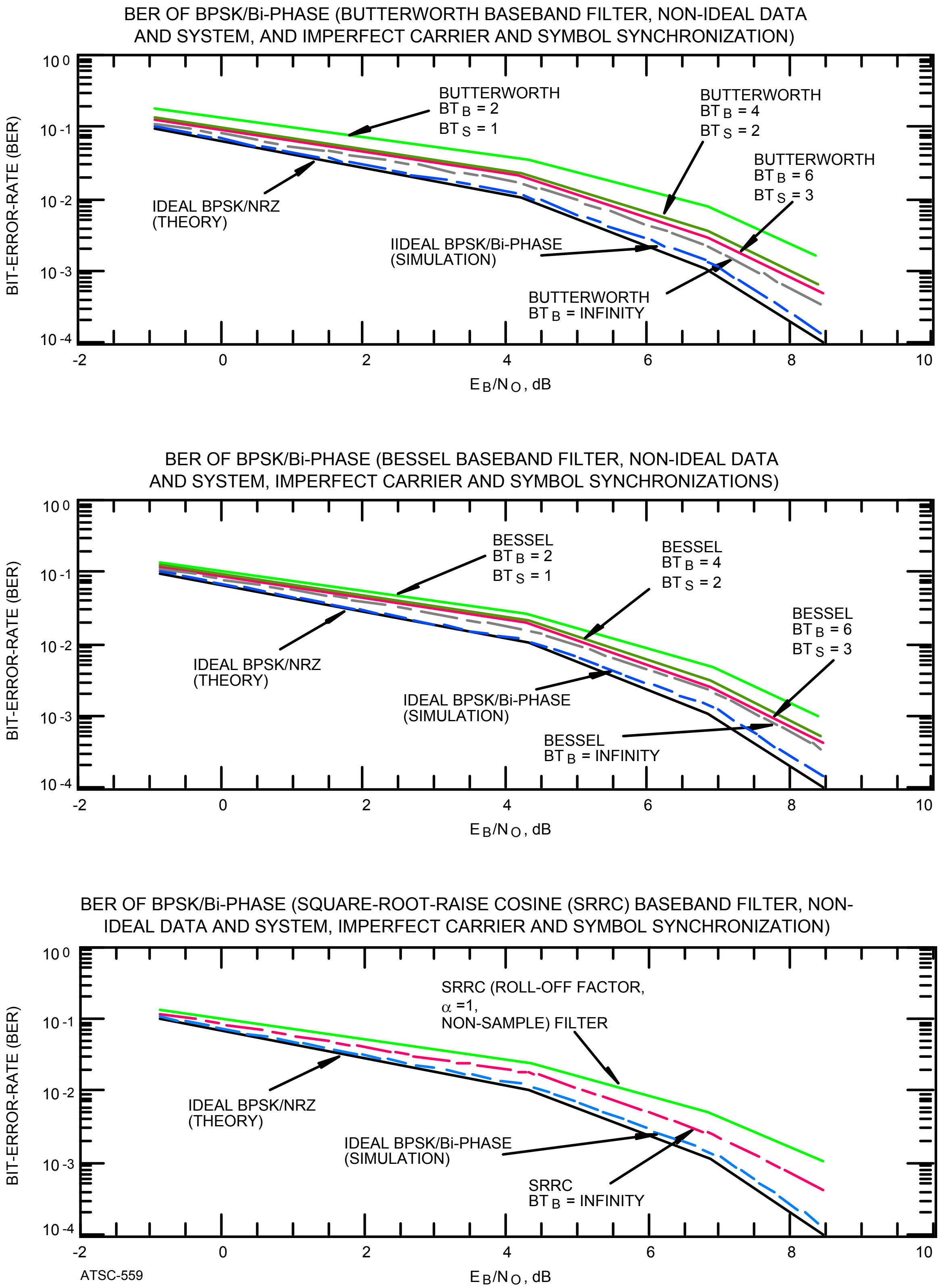


Figure 3.5-1: BPSK/Bi-N Modulation Bit-Error-Rate (BER)

3.5.2 BPSK / Bi-N Modulation Spectra

Figure 3.5-2 contains spectra for this modulation type. As for other modulation types, filtering significantly reduces RF bandwidth requirements. Again the passive Butterworth filter ($BT_S = 2$) appears to offer the best compromise between system complexity and RF bandwidth reduction.

Comparing BPSK/Bi-N and BPSK/NRZ spectra (Figures 3.5-2 and 3.4-2) yields the following observations. First, BPSK/Bi-N modulation approximately doubles the bandwidth. Second, spikes due to phase domain filtering appear at spectrum nulls while spikes resulting from the data imbalance appear at the peaks. Third, baseband filtering also produces a dc component at f_C. Manchester encoding makes it virtually impossible for *data imbalance* to exist making the spike at f_C very small on the unfiltered BPSK/Bi-N curve on Figure 3.5-2. The existence of the small spike at f_C in the unfiltered case results from the use of non-ideal system components.

Contrasting spectra for BPSK/Bi-N modulation (Figure 3.5-2) and PCM/PM/Bi-N modulation (Figure 3.3-2), also shows interesting differences. The broadband residual carrier spectrum is slightly narrower than suppressed carrier spectrum because of the power retained in the RF carrier. Except for the f_C component, the spike amplitudes are approximately the same for the two modulation types.

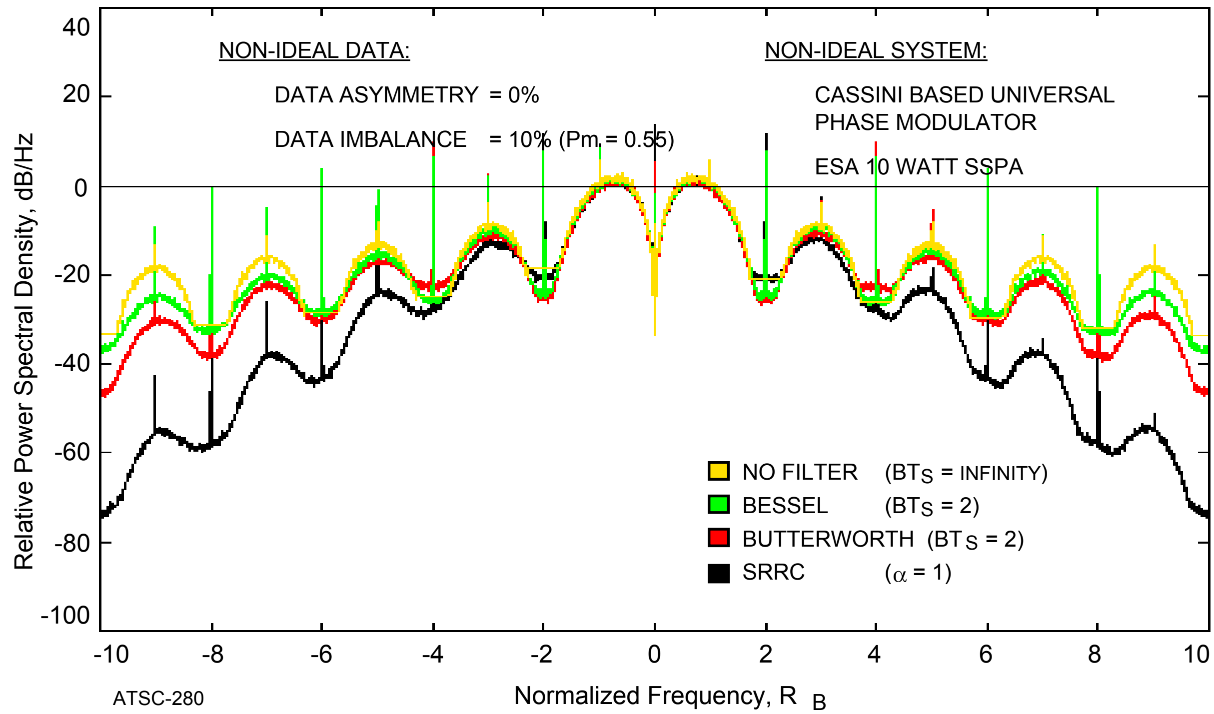
3.5.3 BPSK / Bi-N Modulation Power Containment

With an *occupied bandwidth* of 12 R_B using a Butterworth, $BT_S = 2$ filter, BPSK/Bi-N is the least bandwidth-efficient modulation method in the Phase 3 study. Even with a Square Root Raised Cosine (" = 1) filter, the *occupied bandwidth* is 8 R_B.

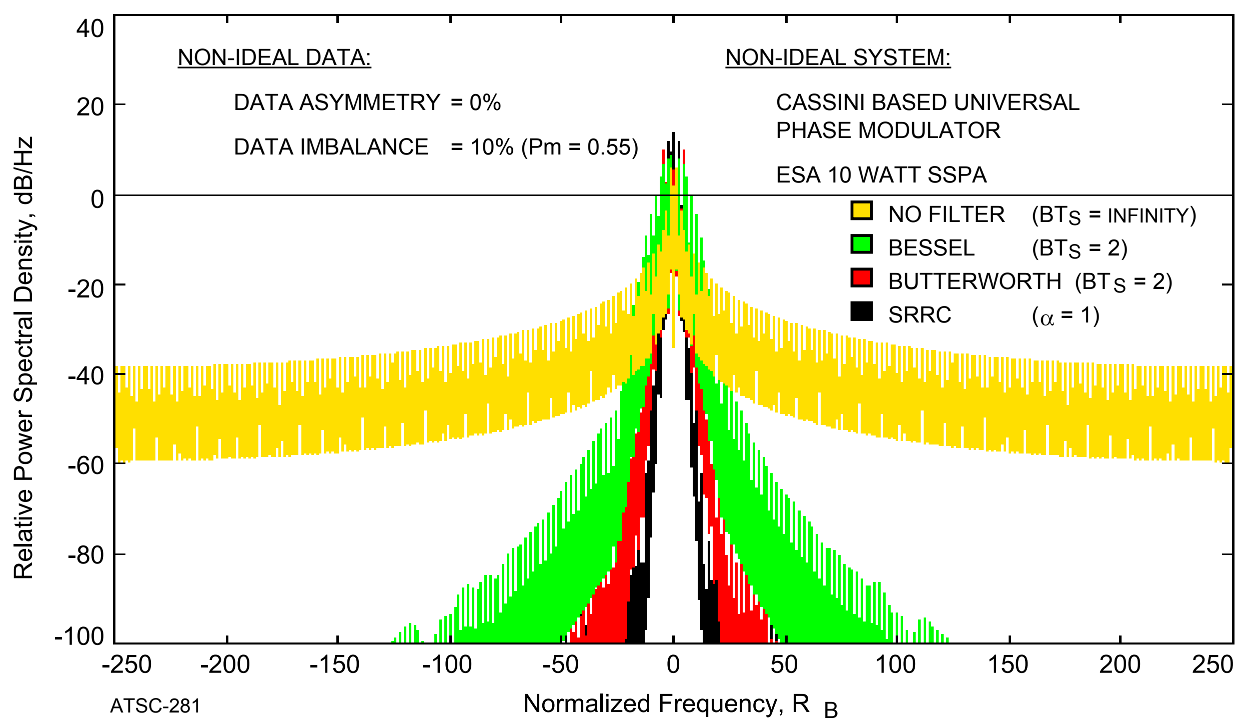
3.5.4 BPSK / Bi-N Modulation Study Conclusions

With its comparatively large bandwidth requirements and its poorer BER performance, BPSK/Bi-N modulation is not likely to find wide application. Its use should be limited to circumstances when the data's symbol transition density is so low that the symbol synchronizer may have difficulty in acquiring or maintaining lock or where suppressed carrier modulation is required with very low data symbol rates.

Generally, space agencies interested in maximizing bandwidth efficiency should avoid use of this modulation type whenever possible. Where data symbol transition densities are so low that one of the NRZ modulation formats is unsuitable, use of BPSK/Bi-N modulation may be unavoidable. Alternatively, space agencies could consider using symbol synchronizers which are not based on a Data Transition Tracking Loop (DTTL) architecture. For example, an open loop design such as the Maximum A Posteriori (MAP) symbol synchronizer [8] will not have difficulty at low transition densities. This alternative symbol synchronizer architecture is particularly attractive for modulation methods such as MSK, GMSK, and FQPSK.



3.5-2a: Fine Detail ($f_{C\pm}$ 10 R_B)



3.5-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.5-2: BPSK/Bi-N Modulation Spectra

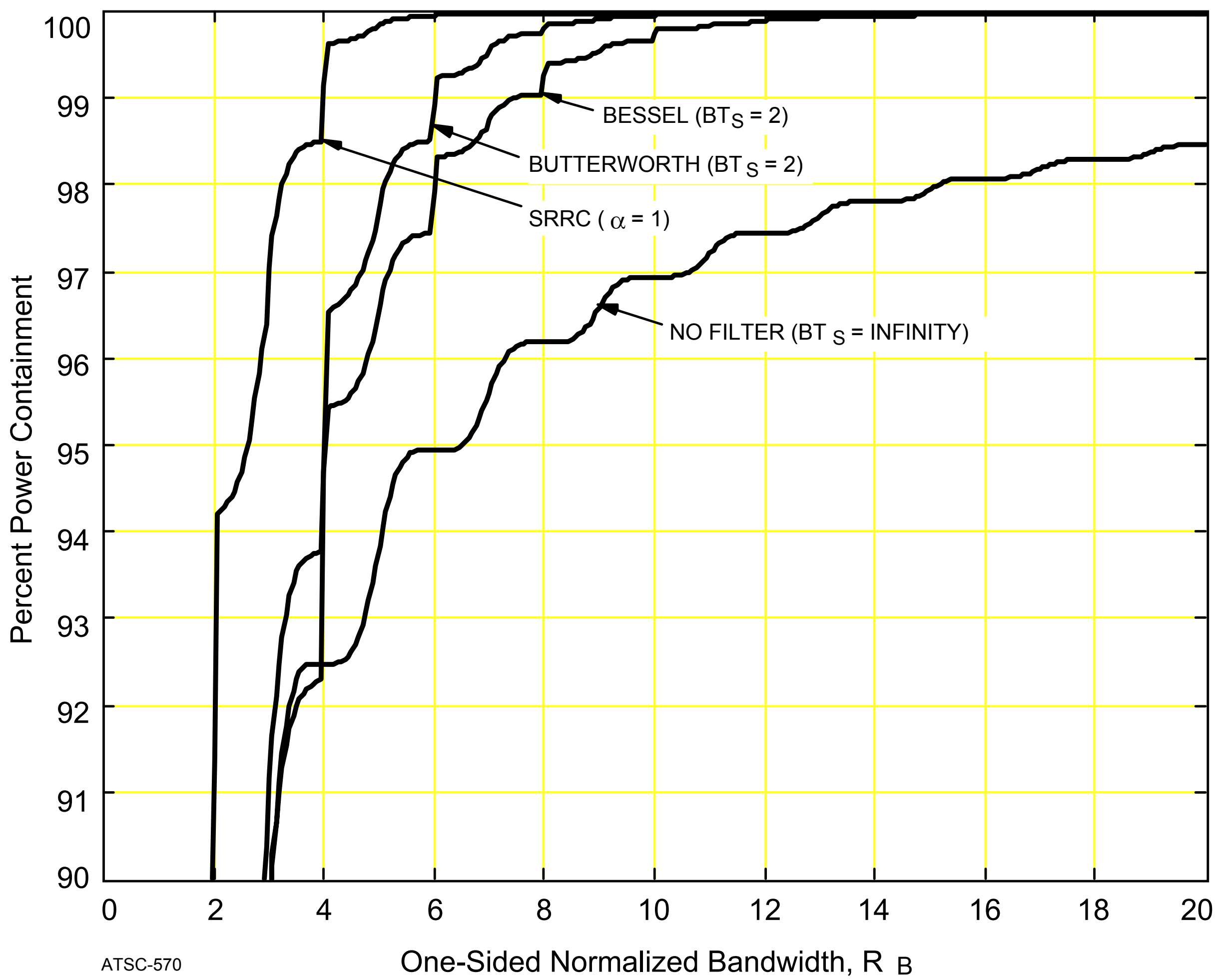


Figure 3.5-3: BPSK/Bi-N Modulation Power Containment

3.6 QPSK MODULATION

Although found less frequently than the modulation types discussed above, QPSK has been used by many CCSDS Space Agencies. It has often found application in high data rate missions operating in the *Earth Exploration Satellite* and the *Meteorological* services.

QPSK can be visualized as two BPSK/NRZ channels having an orthogonal phase relationship, each containing $P_T/2$ transmit power where P_T is the spacecraft's total transmitted power. The resulting four-phase states represent specific information bit pairs. Table 3.6-1 shows the RF carrier phase shift provided by the Universal Phase Modulator (UPM) for the bit-pair combinations.

Table 3.6-1: QPSK Input Data - RF Carrier Phase Relationship

Input Data (bit- pairs)	RF Carrier Phase (degrees)
00	45
01	-45
10	135
11	-135

3.6.1 QPSK Modulation Bit-Error-Rate (BER)

Figure 3.6-1 contains the QPSK BER vs data bit power relationships for the three filter types. With $P_T/2$ transmit power and a data rate of one-half that in each BPSK/NRZ channel, the received signal-to-noise ratio remains unchanged. That is clearly shown by coincidence in the Ideal BPSK/NRZ and Ideal QPSK curves on Figure 3.6-1 which differ by less than 0.1 dB at a BER = 1×10^{-3}.

As the bandwidth is restricted, crosstalk between orthogonal I and Q channels increases, resulting in greater losses. At a $BT_S = 1$, QPSK Filtering Losses become 2.2 to 2.9 dB for Bessel and Butterworth filters respectively. An E_B / N_0 of about 8.3 dB is required to achieve a 1×10^{-3} BER using a Butterworth $BT_S = 2$ filter. BPSK/NRZ modulation achieves the same BER with an E_B / N_0 of only 7.7 dB with a Butterworth ($BT_S = 2$) filter.

3.6.2 QPSK Modulation Spectra

The most obvious difference from BPSK/NRZ appears in the spectra shown on Figure 3.6-2 for QPSK. Filtered QPSK's spectral width is one-half that of BPSK/NRZ (Figure 3.4-2) and one-fourth that of BPSK/Bi-N modulation. Of the traditional phase modulation methods, filtered QPSK is the most bandwidth-efficient.

QPSK is no exception to the general rule that filtering is required. Comparing unfiltered and filtered spectra on Figure 3.6-2b instantly reveals the dramatic increase in bandwidth efficiency from filtering. Square Root raised Cosine filters provide the maximum spectrum efficiency; however, the Butterworth $BT_S = 2$ filter is a close second down to levels 60 dB below the peak sideband amplitude. Considering its simplicity, the passive Butterworth filter is the recommended type.

3.6.3 QPSK Modulation Power Containment

Figure 3.6-3 shows the *occupied bandwidth* of a Butterworth ($BT_S = 2$), filtered signal to be approximately 3.5 R_B. Even without filtering, it is possible to obtain an *occupied bandwidth* of about 10 R_B. It is clear from Figure 3.6-3 why QPSK has been the modulation method of choice for medium and high data rate missions. It may still be a good choice for some medium data rate projects.

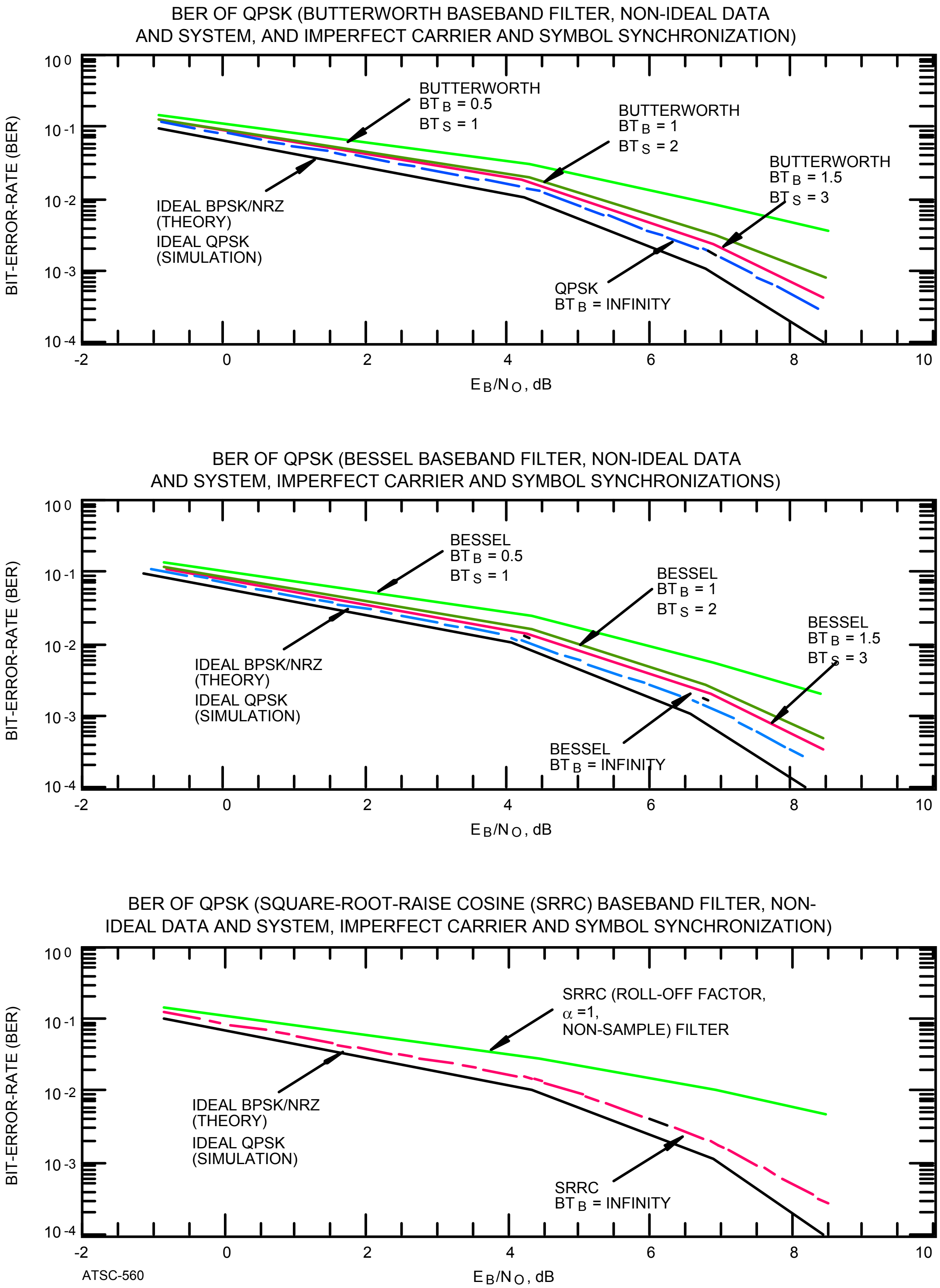
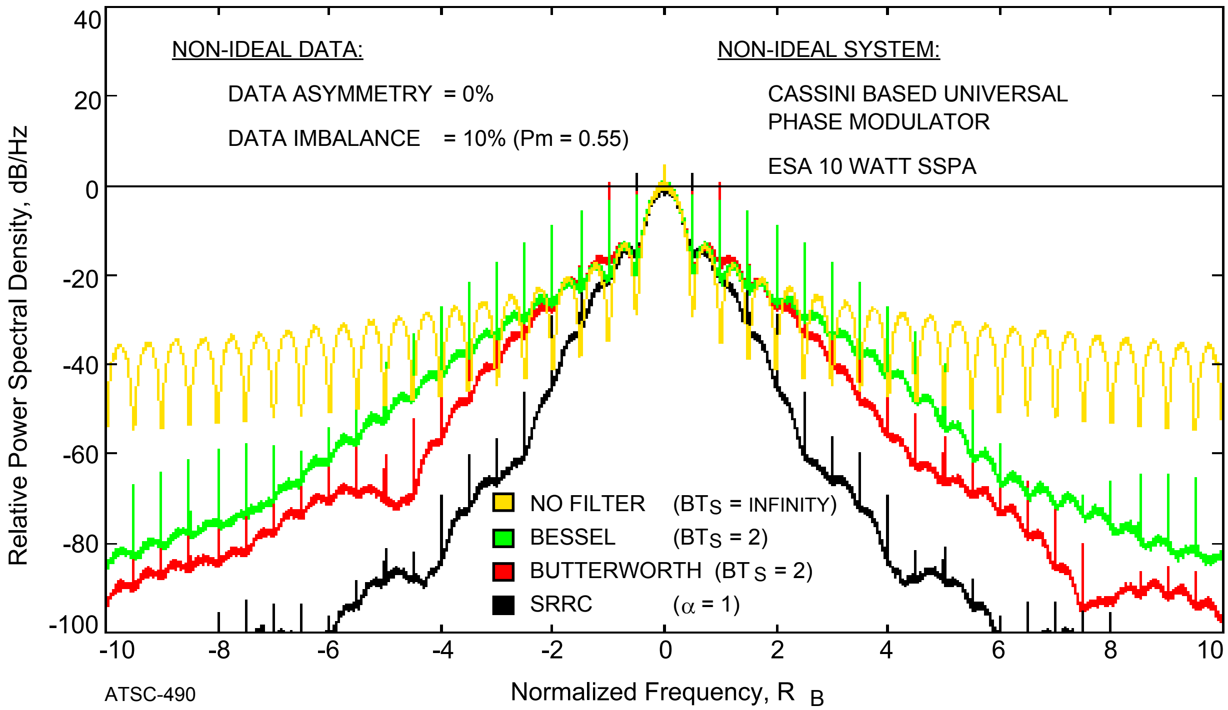
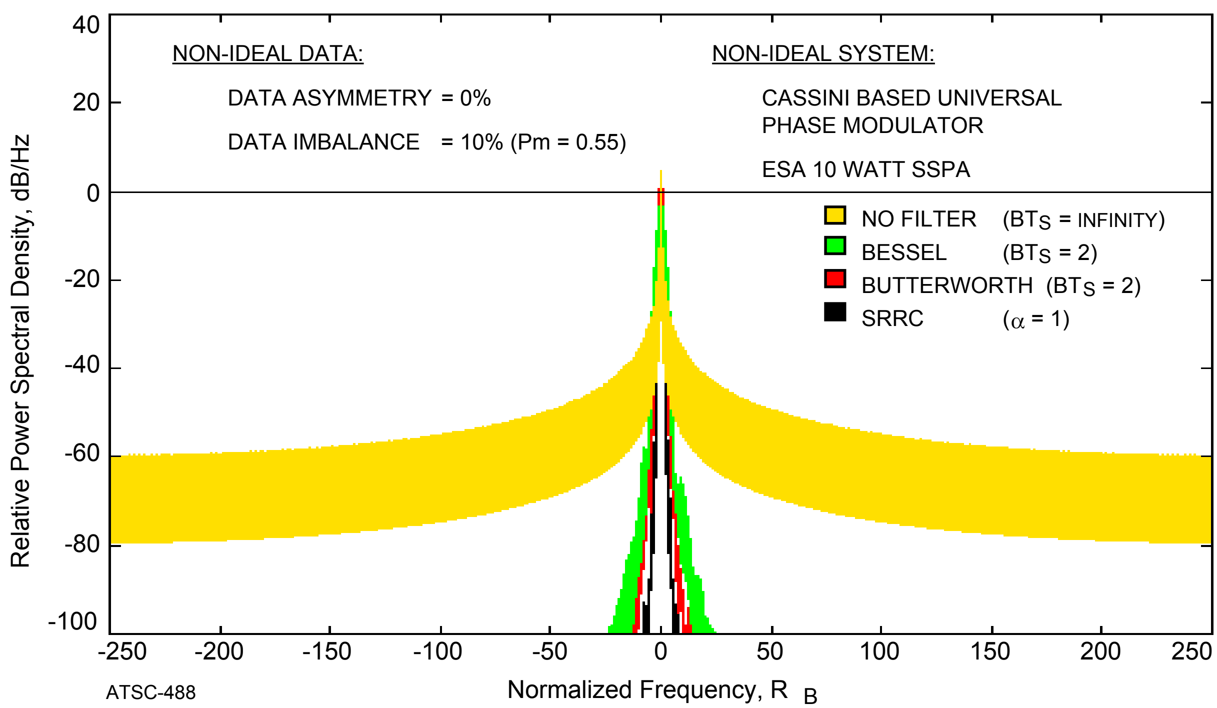


Figure 3.6-1: QPSK Modulation Bit-Error-Rate



3.6-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.6-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.6-2: QPSK Modulation Spectra

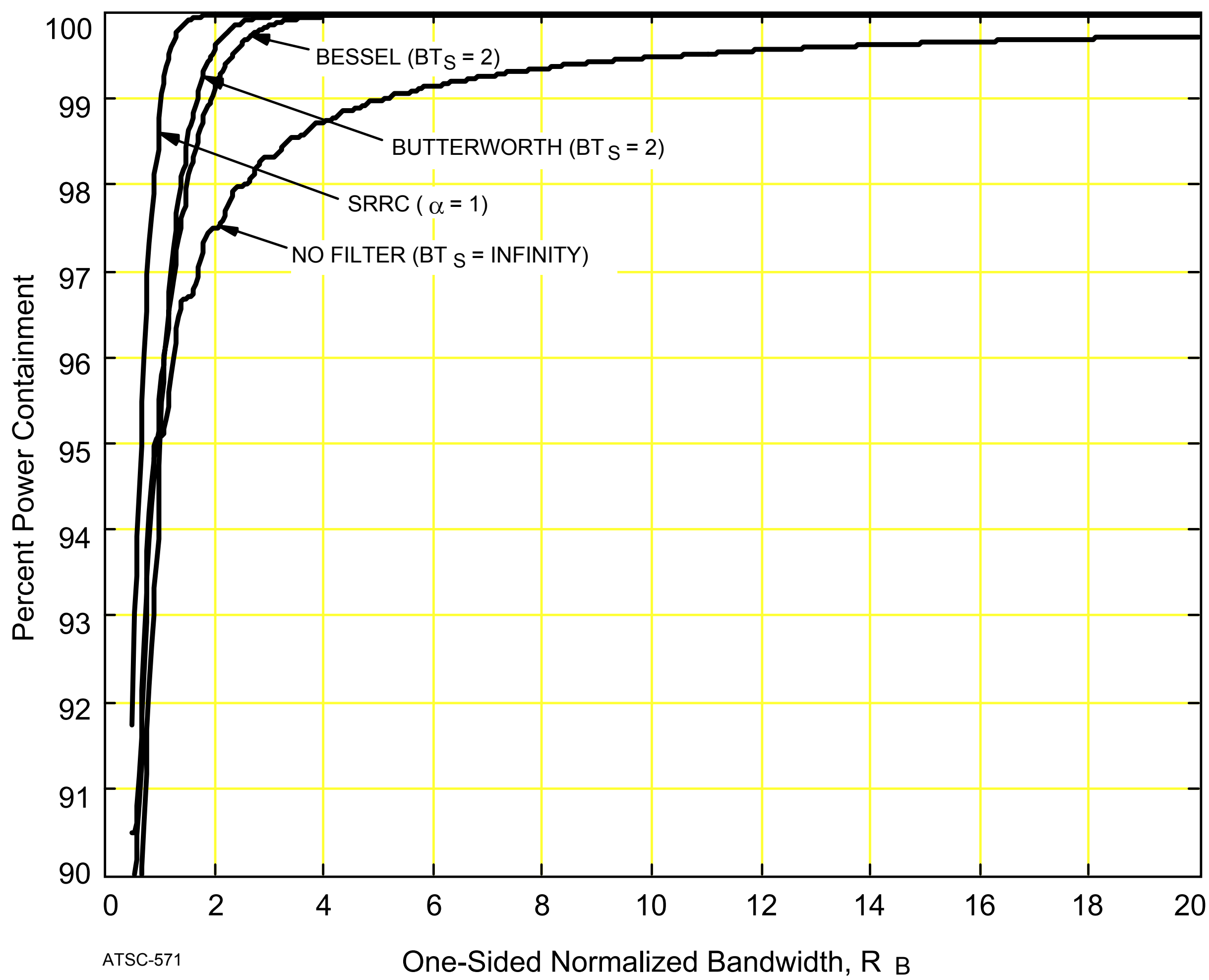


Figure 3.6-3: QPSK Modulation Power Containment

3.6.4 QPSK Modulation Study Conclusions

QPSK modulation has been used in recent years for medium and high telemetry data rate transmissions. Viewed as two orthogonal BPSK/NRZ channels, QPSK bit-error-rate performance is equal to that of BPSK/NRZ with one-half of the data rate on each channel. Like all suppressed carrier systems, a somewhat higher Costas loop Signal-to-Noise Ratio is required for proper operation than is the case for a residual carrier phase-locked loop.

QPSK should receive serious consideration for telemetry systems operating in the 200 ks/s - 2 Ms/s symbol rate range. However, the existence of newer, much more bandwidth-efficient, modulation schemes should relegate QPSK to medium data rate missions, at least in those space agencies truly concerned with minimizing their RF spectrum needs. This is particularly true for missions operating in the *Earth Exploration Satellite* and the *Meteorological* services.

3.7 OQPSK MODULATION

Offset QPSK modulation is purported to generate a more compact spectrum than QPSK in the presence of non-linear amplification. Modulation sidebands are said to decline more rapidly than for QPSK. Absent this non-linearity, OQPSK and QPSK spectra are identical.

I and Q in a OQPSK system are customarily treated as separate, independent channels with a ½ symbol-time offset between the I-channel phase change and the Q-channel phase change. Here, OQPSK is treated as an alternative to QPSK. The simulated transmitting system used the Universal Phase Modulator (UPM).

The UPM's implementation does not permit proper OQPSK operation. Where a 180 degree phase change is occasioned by the data, an intermediate rest level of either ± 90 degrees is established for one-half symbol-time. Restricting the phase change reduces sideband generation in non-linear system elements. To some degree, this pseudo OQPSK modulation system approximates a filtered QPSK modulated system by limiting sequential phase changes to ± 90 degrees.

OQPSK filtering is the same as for QPSK modulation. Butterworth and Bessel filters having BT_S = 1, 2, and 3 were used. As with the other modulation methods, all spectra are based on a Butterworth BT_S = 2 baseband filter. Unfortunately, the results were less than satisfactory.

3.7.1 OQPSK Modulation Bit-Error-Rate (BER)

Figure 3.7-1 contains Bit-Error-Rate (BER) data for OQPSK. With no filtering (i.e., BT_S = 4), the performance is equivalent to that of a QPSK system. However, with the UPM, OQPSK BER performance deteriorates sharply as the filter's bandwidth decreases. With a Butterworth (BT_S = 2) filter, an E_B / N_0 . 8.7 dB is required for a 1×10^{-3} BER. Given the modulator problems, these test data are not sufficient to discriminate between the two modulation types.

3.7.2 OQPSK Modulation Spectra

Determining whether this variant of OQPSK is a viable modulation type is no easier using the spectra shown on Figure 3.7-2. Interestingly, there is virtually no difference between the unfiltered spectra for OQPSK and QPSK (Figure 3.5-2), even with the non-linear power amplifier. The modulator's unsuitability makes it difficult to comment on the spectra.

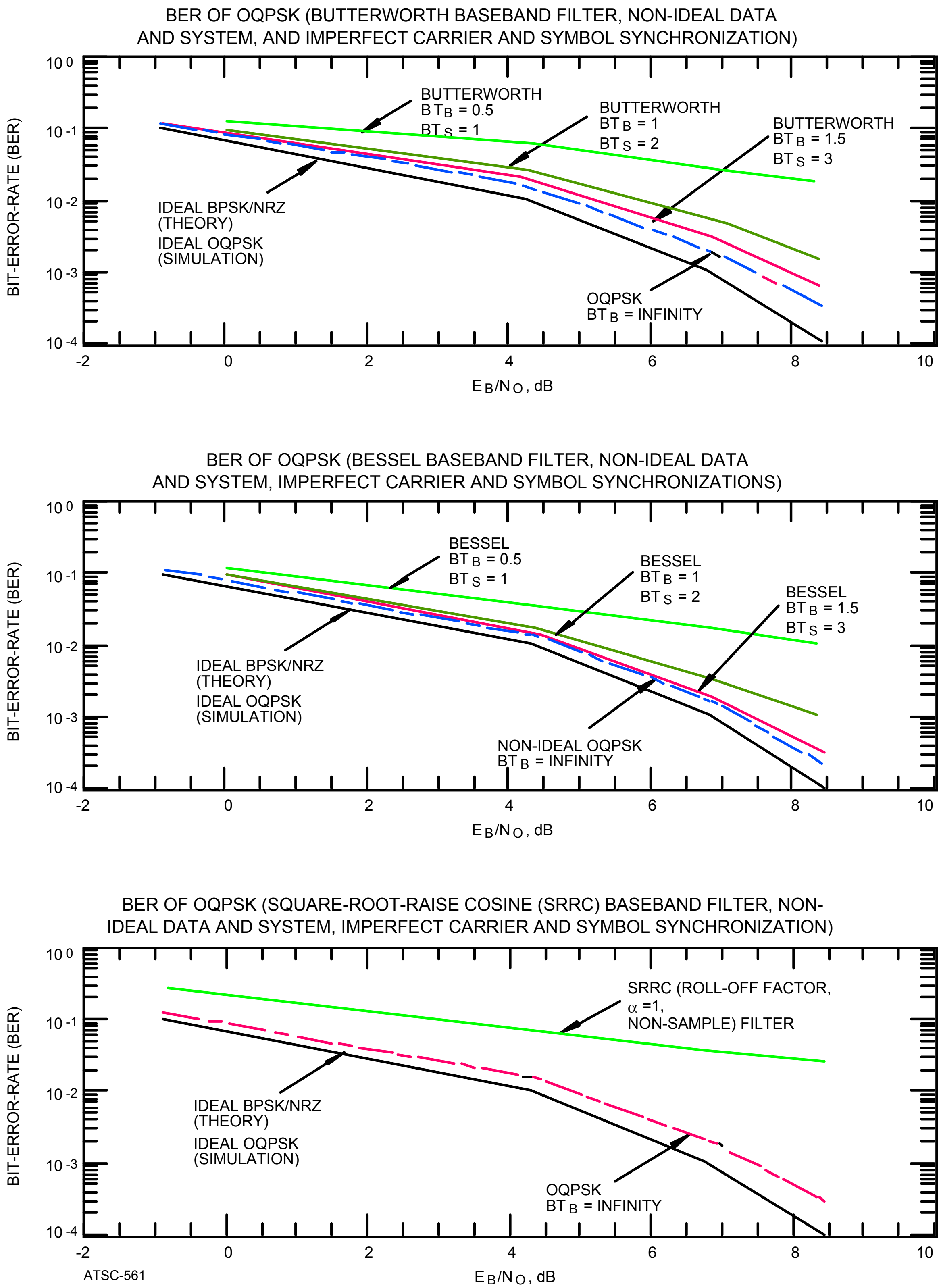
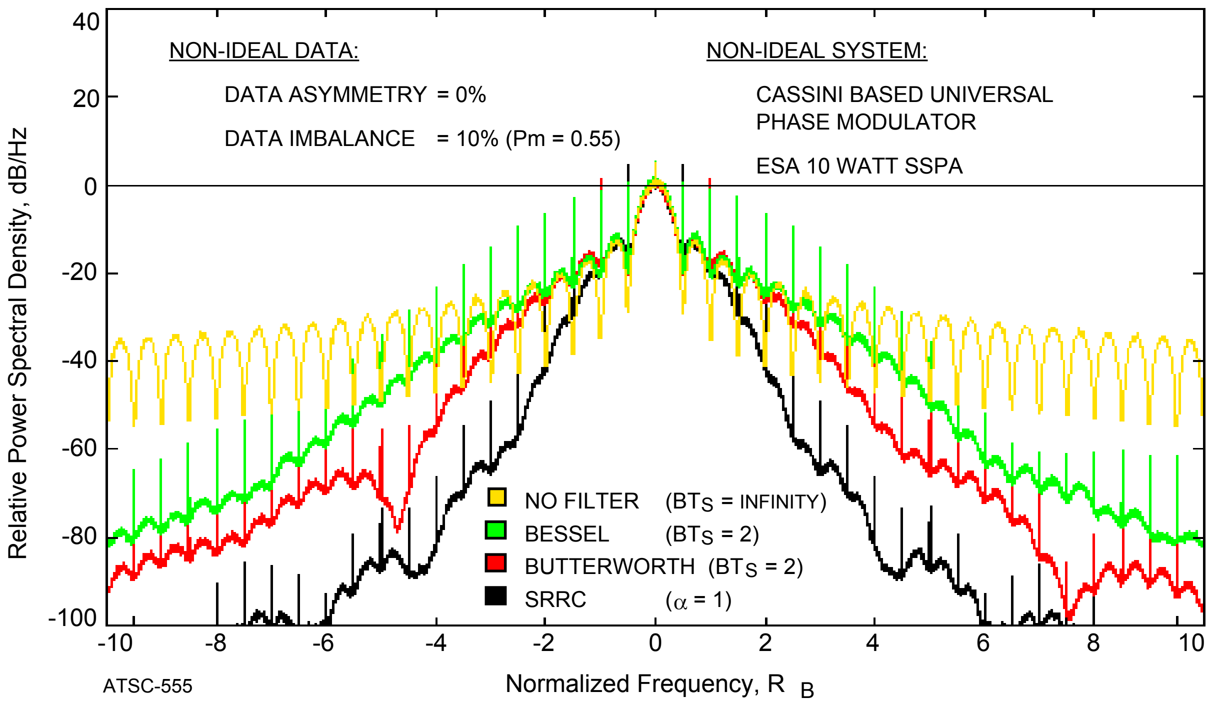
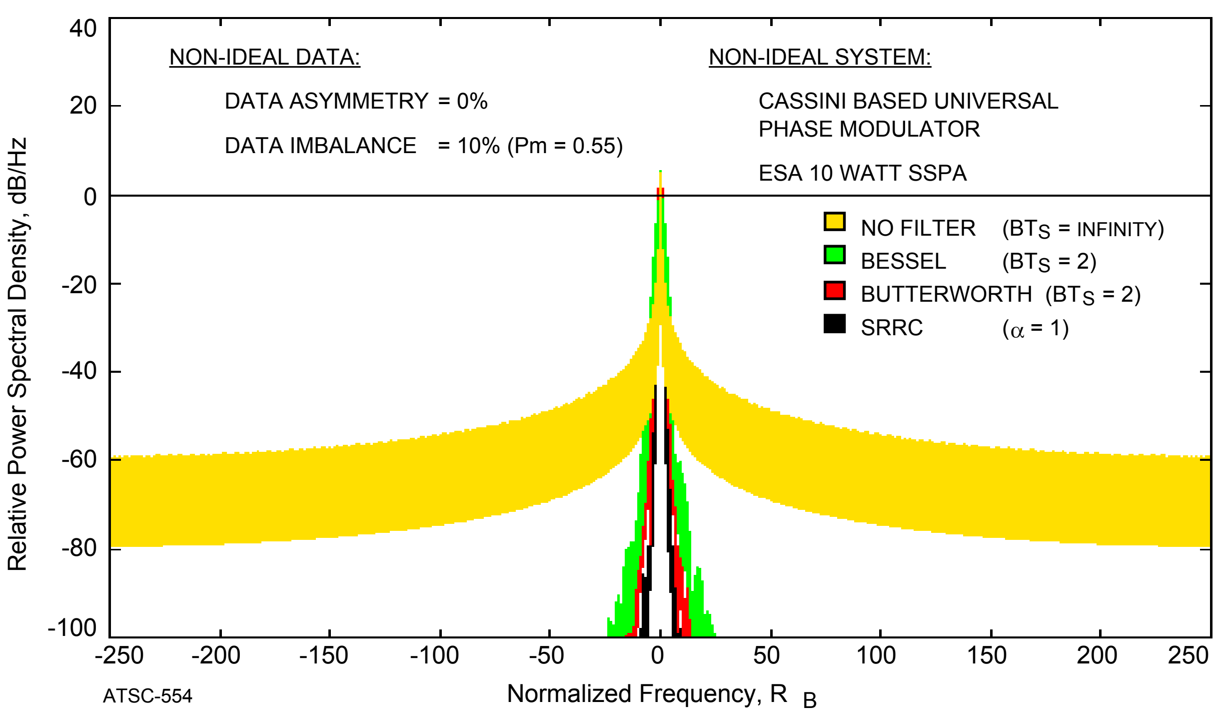


Figure 3.7-1: OQPSK Modulation Bit-Error-Rate



3.7-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.7-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.7-2: OQPSK Modulation Spectra

3.7.3 OQPSK Modulation Power Containment

Power containment, figure 3.7-3 is virtually identical to that for QPSK. With a Butterworth (BT_S = 2) filter, the *occupied bandwidth* is about 3.5 R_B. No power containment differences were found between OQPSK and QPSK.

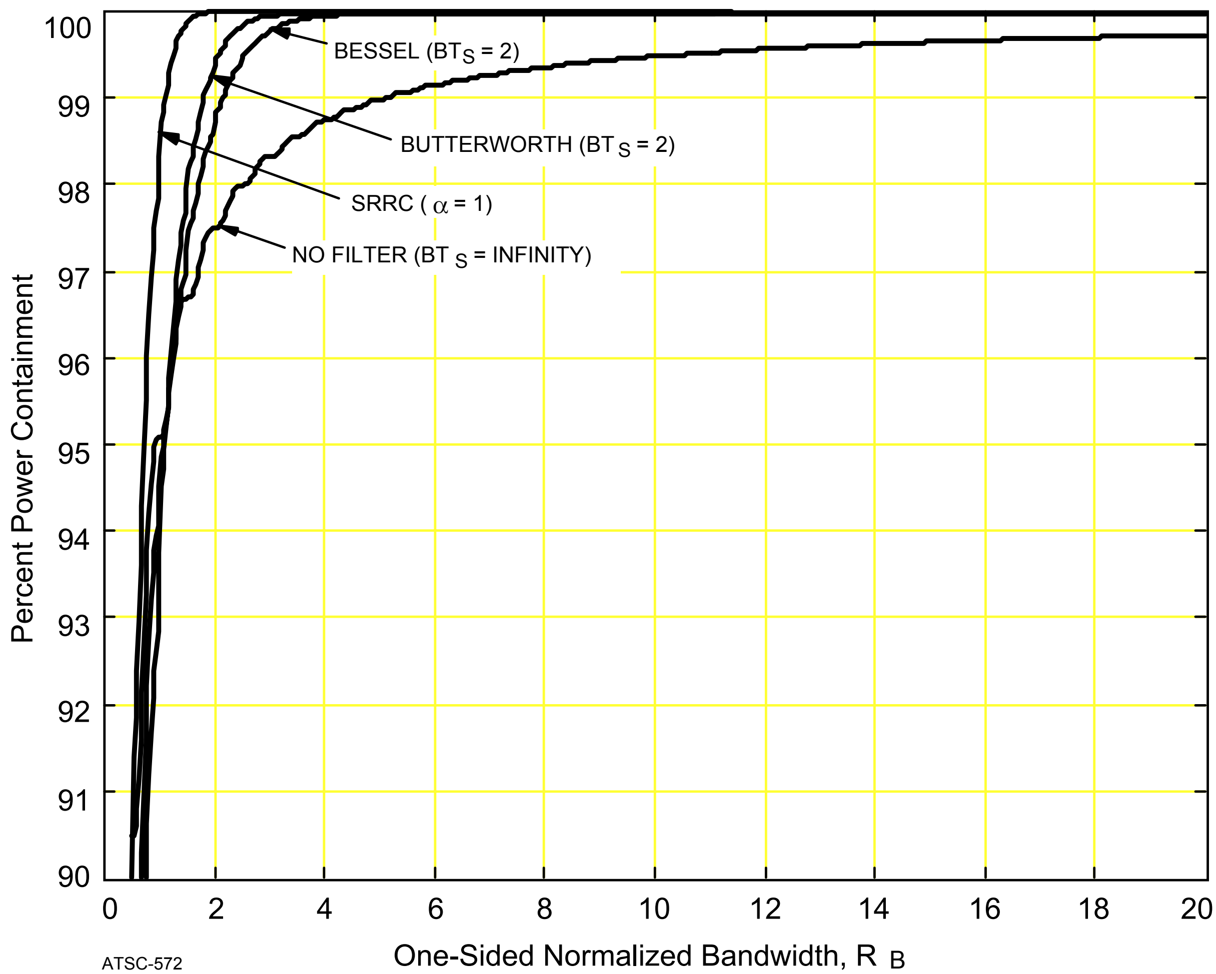


Figure 3.7-3: OQPSK Modulation Power Containment

3.7.4 OQPSK Modulation Study Conclusions

No discernable bandwidth differences between OQPSK and QPSK modulation were found, despite the use of non-linear system elements such as a saturated power amplifier. However, the OQPSK BER performance deteriorates sharply as the filter bandwidth decreases. This finding could be the result of an inadequate phase modulator. With baseband filtering, the UPM's transitions require an excessively long time with an intermediate dwell state. A true OQPSK modulation evaluation requires a different phase modulator design. At this time there is not sufficient extrinsic evidence of OQPSK's superiority to warrant modulator modifications or additional investigations.

3.8 CONTINUOUS PHASE MODULATION (CPM)

Two modulation types, not commonly used by the CCSDS Space Agencies, have been included in Phase 3 for comparative purposes. Both are in a class termed Continuous Phase Modulation (CPM). As the name implies, phase changes are gradual and without discontinuities. The resulting RF spectrum is inherently narrower than that for the unfiltered phase modulation methods discussed above. Two variants of CPM are included in this study: Minimum Shift Keying (MSK) and Gaussian Minimum Shift Keying (GMSK). Neither modulation scheme has been widely used by space agencies. Because they are essentially the same, they are grouped together in this section.

MSK is unfiltered while GMSK adds a baseband Gaussian filter to the modulator. The Universal Phase Modulator (UPM) and the ARX II receiver are not suitable for CPM. Therefore, the simulation system used for CPM studies deviates from that described in Section 2.1 above. Modifications include an ideal frequency modulator from the SPW library and an ideal receiver with perfect carrier tracking and symbol synchronization.

Demodulation was based on a paper showing that GMSK can be decomposed into a series of amplitude pulses.[9] The Phase 3 study receiver simulation model is predicated on a paper describing how the optimum receiver's four or eight matched filters can be reduced to only two filters, a matched filter followed by a Wiener filter to reduce ISI.[10]

3.8.1 MSK and GMSK Modulation Bit-Error-Rate (BER)

Figure 3.8-1 contains Bit-Error-Rate curves for MSK and GMSK. GMSK studies included two separate filters with $BT_S = 0.5$ (equivalent to $BT_B = 0.25$) and $BT_S = 1$ (equivalent to $BT_B = 0.5$) Since these bandwidths are smaller than those for the Butterworth and Bessel filters ($BT_S = 1, 2, 3$), one can anticipate that the end-to-end losses should be higher and the RF spectrum will be narrower.

Unlike previous modulation studies having three plots, one for each filter type, here there is but one. MSK is unfiltered and GMSK includes a Gaussian filter with two bandwidths ($BT_S = 0.5, 1$). For simplicity, these, along with an ideal BPSK/NRZ reference curve, are placed on a single BER graph. Note that the E_B / N_0 required for a 1×10^{-3} BER is 7.3 - 8.2 dB which compares favorably with BPSK/NRZ, even with a Gaussian filter bandwidth $BT_S = 0.5$. Losses can be expected to increase when a non-ideal modulator and receiver are employed; however, Figure 3.8-1 was generated using the ESA power amplifier operating in full saturation.

3.8.2 MSK and GMSK Modulation Spectra

Most MSK and GMSK applications have been in Personal Communication Systems (PCSs). Spacecraft telemetry transmission systems have avoided GMSK because of demodulation and synchronization difficulties. Often termed frequency modulation, MSK and GMSK were included because of their inherently narrow spectral bandwidths. Unlike the other modulation types, MSK is unfiltered and sidelobes are reduced by avoiding phase change discontinuities. Figure 3.8-2 shows spectra for unfiltered, ideal BPSK/NRZ (reference), MSK, and GMSK using the two filter bandwidths. No discrete components are present in MSK or GMSK spectra despite baseband filtering.[11]

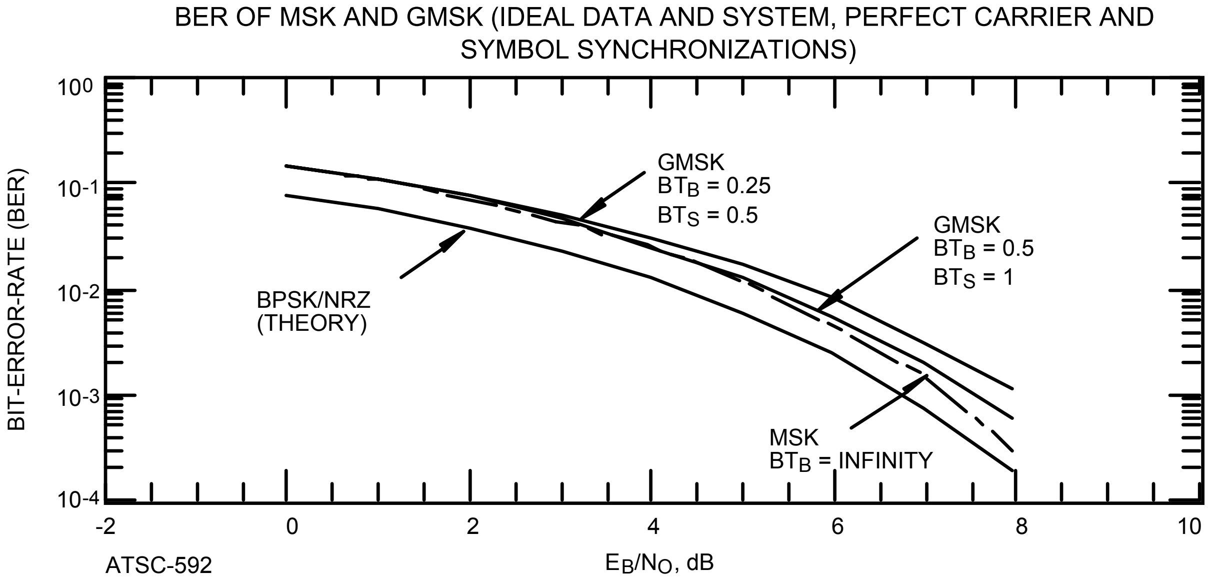


Figure 3.8-1: MSK / GMSK Modulation Bit-Error-Rate (BER)

Figure 3.8-2 shows MSK modulation to be significantly more bandwidth-efficient than the unfiltered BPSK/NRZ reference, reaching a level 60 dB below the peak sideband amplitude at ± 8 R_B. Its lack of discrete spectral components makes it attractive for space telemetry applications.

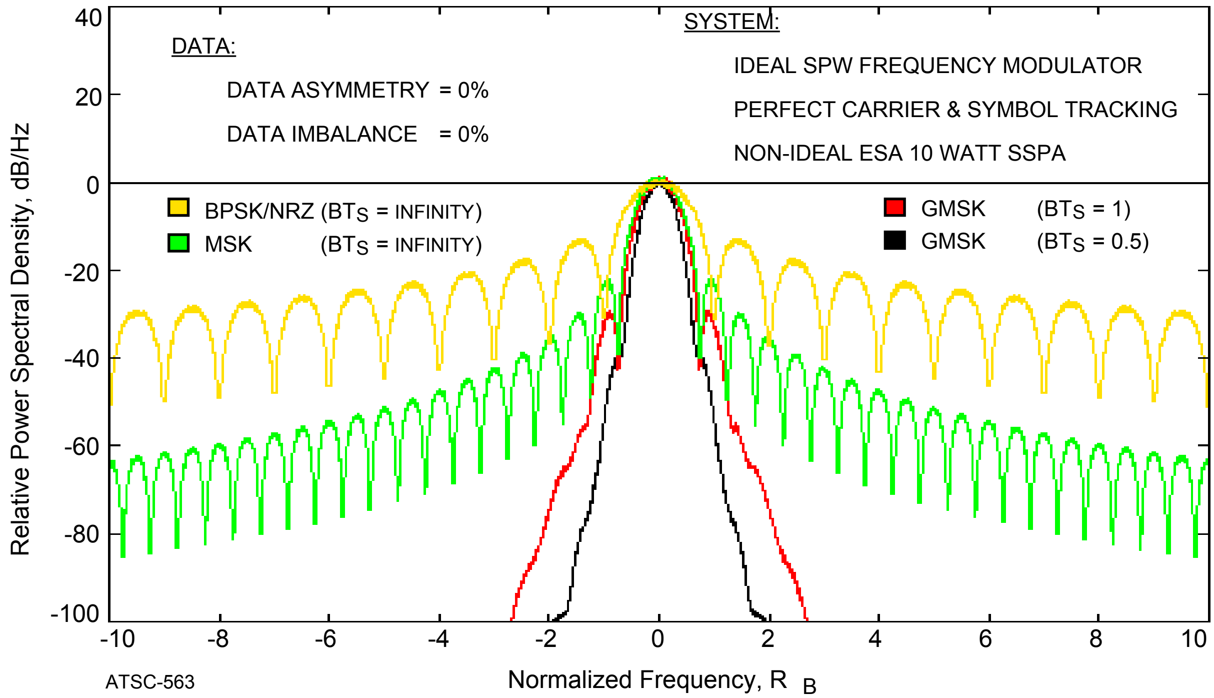
However, from Figure 3.8-2 it is apparent that MSK modulation is of little interest when compared to GMSK. GMSK modulation is significantly more bandwidth-efficient than any other method considered previously. For example, it is 2 to 6 times more bandwidth-efficient than filtered QPSK modulation, depending upon the specific filter bandwidths selected. When coupled with its BER performance, GMSK should be seriously considered for high and very high data rate missions.

3.8.3 MSK / GMSK Modulation Power Containment

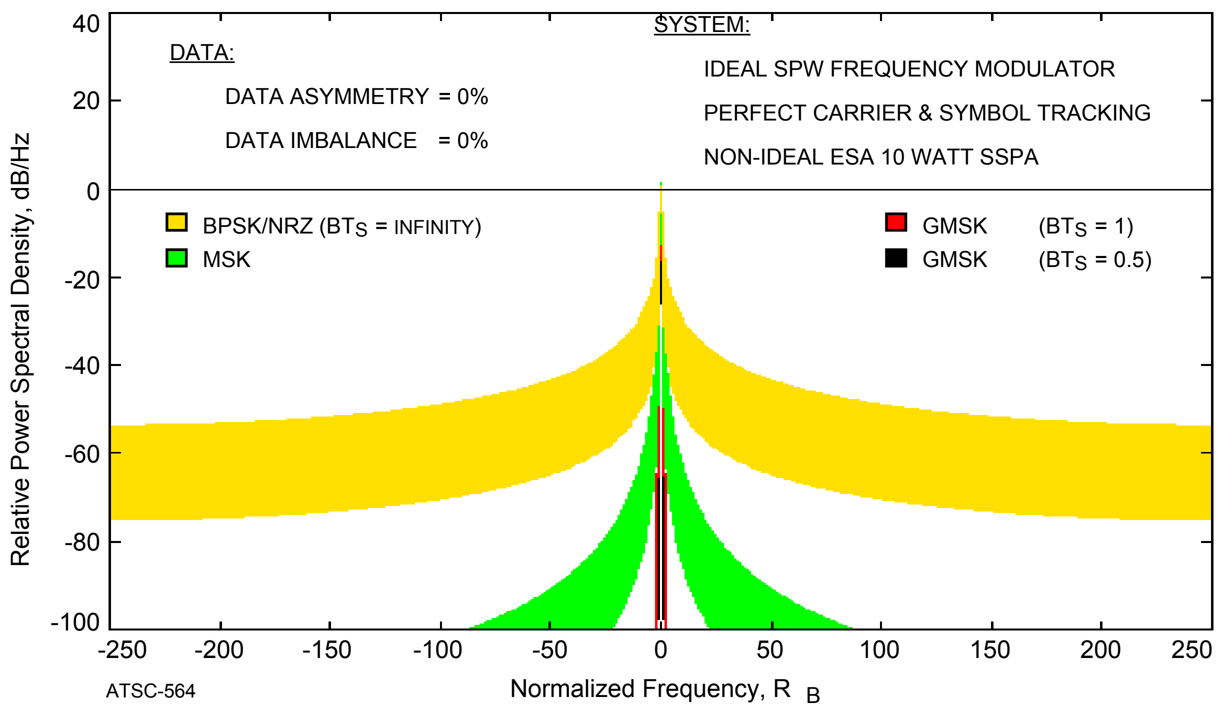
Figure 3.8-3, Power Containment, supports the finding that GMSK has a high bandwidth efficiency. *Occupied bandwidth* is difficult to read, because of its small value, but it appears to be less than 1.2 R_B for both filter bandwidths. This represents a 16-times improvement over the unfiltered [reference] BPSK/NRZ modulation and a 5-fold efficiency increase over filtered BPSK/NRZ.

3.8.4 MSK / GMSK Modulation Study Conclusions

Clearly, space agencies interested in RF spectrum efficiency should seriously consider GMSK modulation. This is particularly true for high and very high data rate missions. Unlike the phase modulation types described above, GMSK requires new modulator, demodulator, and symbol synchronizer designs. In that respect, this recommendation departs from one of the *Efficient Modulation Methods Study* guidelines: *that only simple modifications to existing Earth station equipment are permitted for any recommended modulation method*. However, GMSK's bandwidth efficiency is too great to ignore and a departure from the guideline is warranted.



3.8-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.8-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.8-2: MSK / GMSK Modulation Spectra

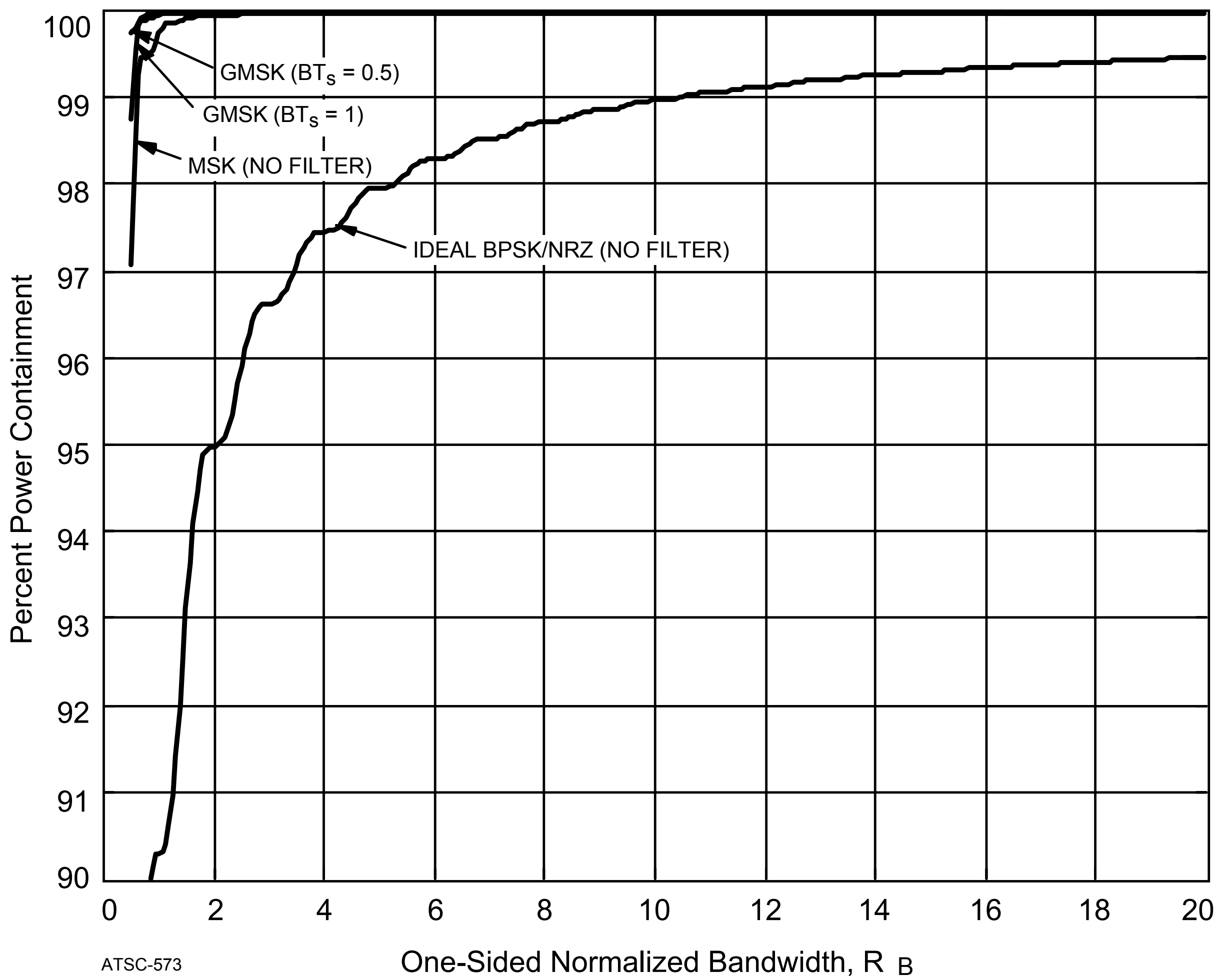


Figure 3.8-3: MSK / GMSK Modulation Power Containment

3.9 8-PHASE SHIFT KEYED (8-PSK) MODULATION

8-PSK modulation is not currently used by CCSDS Space Agencies. NASA Goddard Space Flight Center (GSFC) and their contractor New Mexico State University (NMSU) have devoted a substantial effort to understanding this modulation method.[12, 13] 8-PSK transmits three data bits simultaneously rather than just two data bits as in QPSK.

For study consistency with other phase modulation studies, a complete transmitting and receiving system needed to be simulated. The Universal Phase Modulator is capable of 8-PSK modulation and the transmitting system, including the ESA power amplifier, was used for this evaluation.

The eight possible state vector phases in 8-PSK modulation cannot be orthogonal as in the case of QPSK. Therefore, the ARX II receiver was modified, as shown in Figure 2.3-2, to demodulate an 8-PSK signal by adding signal squaring circuits to the Costas Loop. These devices also squared the noise compromising the system's performance. Inserting a filter in the modulator further degrades system performance because non-orthogonality increases crosstalk between phase states.

3.9.1 8-PSK Modulation Bit-Error-Rate (BER)

Losses are evident in Figure 3.9-1 showing the Bit-Error-Rate performance for 8-PSK modulation. Relative to ideal BPSK/NRZ modulation, even an ideal (lossless) 8-PSK system imposes heavy performance penalties. Ideal 8-PSK requires an E_B / N_0 of 9.5 - 10 dB to attain a BER = 1 x 10^{-3}. When a Butterworth BT_S = 3 filter is added, the required E_B / N_0 rises to 11.5 dB. Compared to the E_B / N_0 of about 8 dB, needed for a filtered non-ideal QPSK system at the same BER, it is clear that 8-PSK is not a useful modulation method in power limited applications. Losses using a Square Root Raised Cosine (" = 1) filter were so great that the plot is not even included in this report.

Excessive losses result from the non-orthogonal relationship between phase states. This simulation shows that inherent 8-PSK modulation losses are unlikely to be acceptable in most applications, even without filtering.

NMSU studies found that filtered 8-PSK modulation BER rate performance improved in non-constant amplitude applications. The Universal Phase Modulator produces a nearly constant envelope signal. That characteristic results in the narrowest RF spectrum. Utilizing a non-constant envelope spectrum may improve the BER performance at the expense of spectrum width.

3.9.2 8-PSK Modulation Spectra

Notwithstanding the system losses, spectrum advantages of simultaneously transmitting three data bits is clearly evident in Figure 3.9-2. 8-PSK modulation with a Butterworth filter having a BT_S = 2 produces the most compact RF spectrum of any phase modulation method reviewed thus far. A BT_S =2 was used for consistency with studies of the other modulation types.

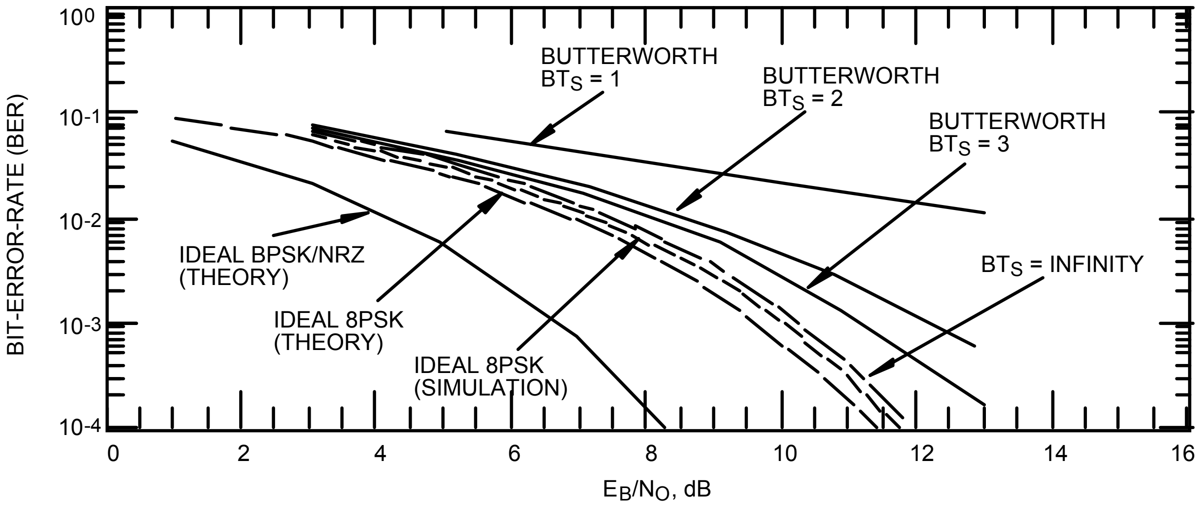
Figure 3.9-2 also demonstrates that filtering will be needed. The unfiltered spectrum (top) is very similar to that for unfiltered QPSK. 8-PSK provides a 1.8 dB improvement in data rate over QPSK and the spectral improvement appears to be on the same order.

3.9.3 8-PSK Modulation Power Containment

Power Containment curves, Figure 3.9-3, show the *occupied bandwidth* to be about 2.4 R_B when using a Butterworth BT_S = 2 filter. This bandwidth will increase with a BT_S = 3 filter which is required to avoid the additional 1 dB loss.

3.9.4 8-PSK Modulation Study Conclusions

Results of this study show 8-PSK modulation to be of little value for most space telemetry data transmissions. While 8-PSK does provide a marginally narrower spectrum, system losses make the modulation type unsuitable for most Category A missions. 8-PSK modulation may be attractive in strong signal applications where system losses are of little importance.



BER OF 8PSK (BESSEL BASEBAND FILTER, NON-IDEAL DATA AND SYSTEM,

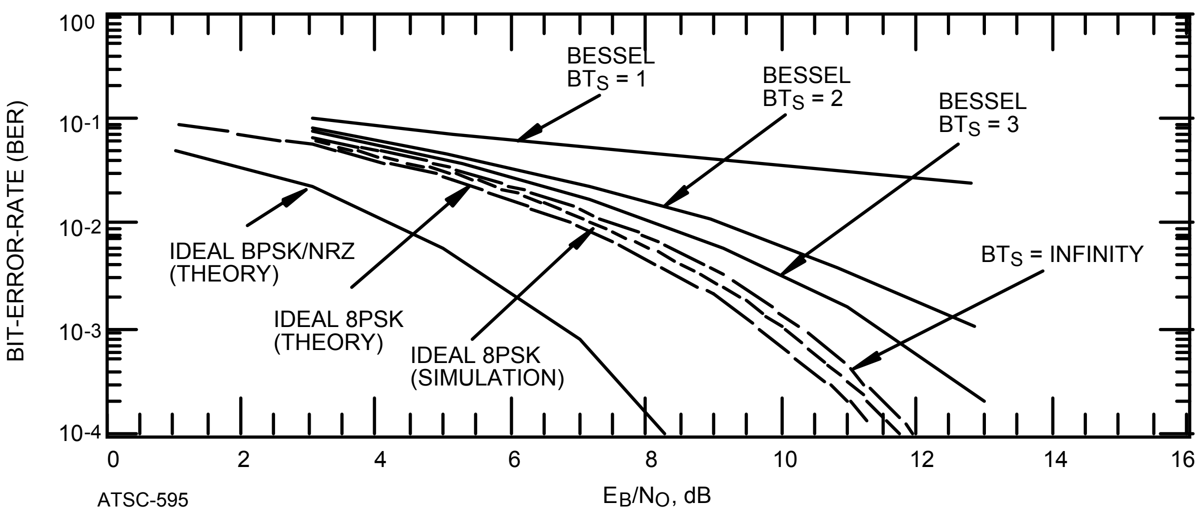
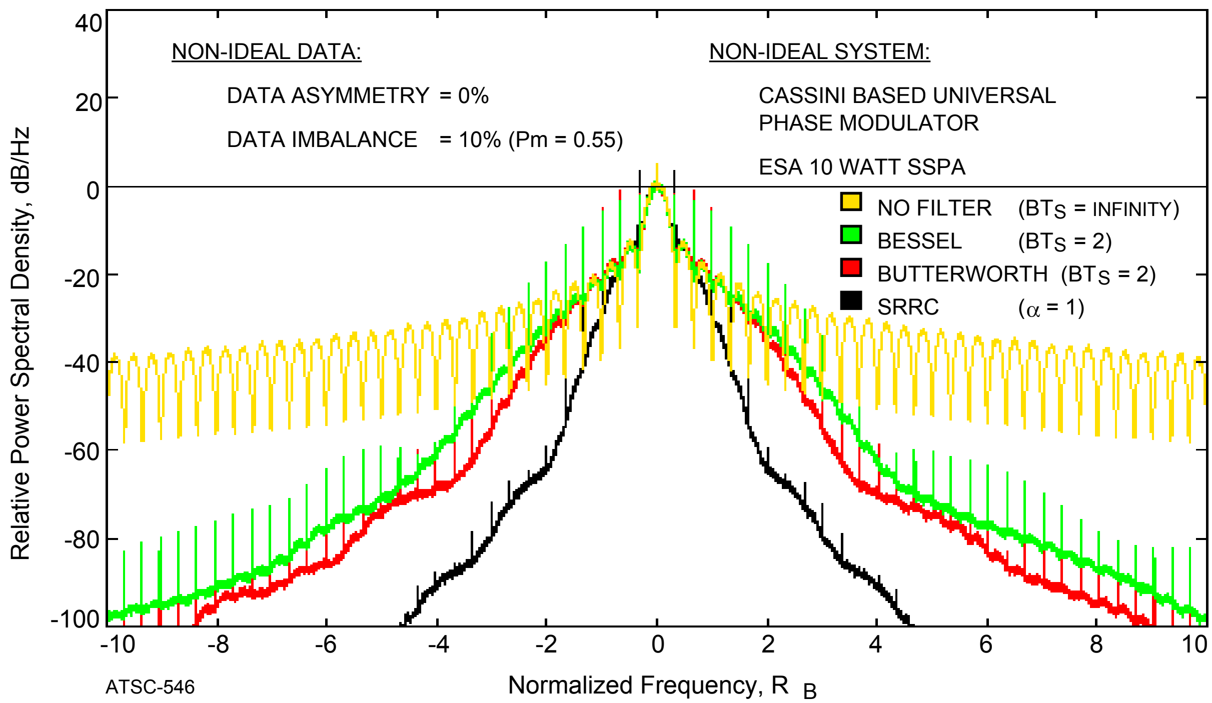
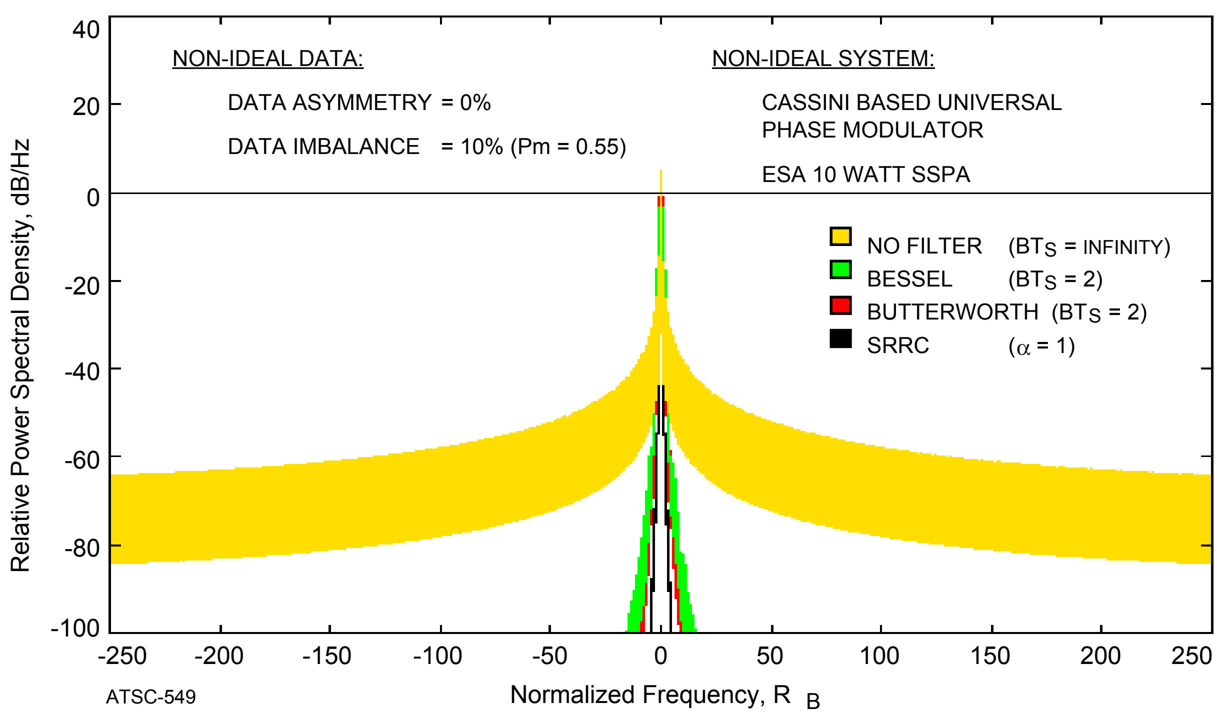


Figure 3.9-1: 8-PSK Modulation Bit-Error-Rate

8-PSK modulation and demodulation can be accomplished by modifing space agencies' existing spacecraft and Earth station hardware. In this regard, 8-PSK modulation does comply with one of the *Efficient Modulation Methods Study* guidelines. However, even if it were possible to construct a lossless receiver, the performance penalty, compared to GMSK and FQPSK-B modulation, is too high to warrant further consideration.



3.9-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.9-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.9-2: 8-PSK Modulation Spectra

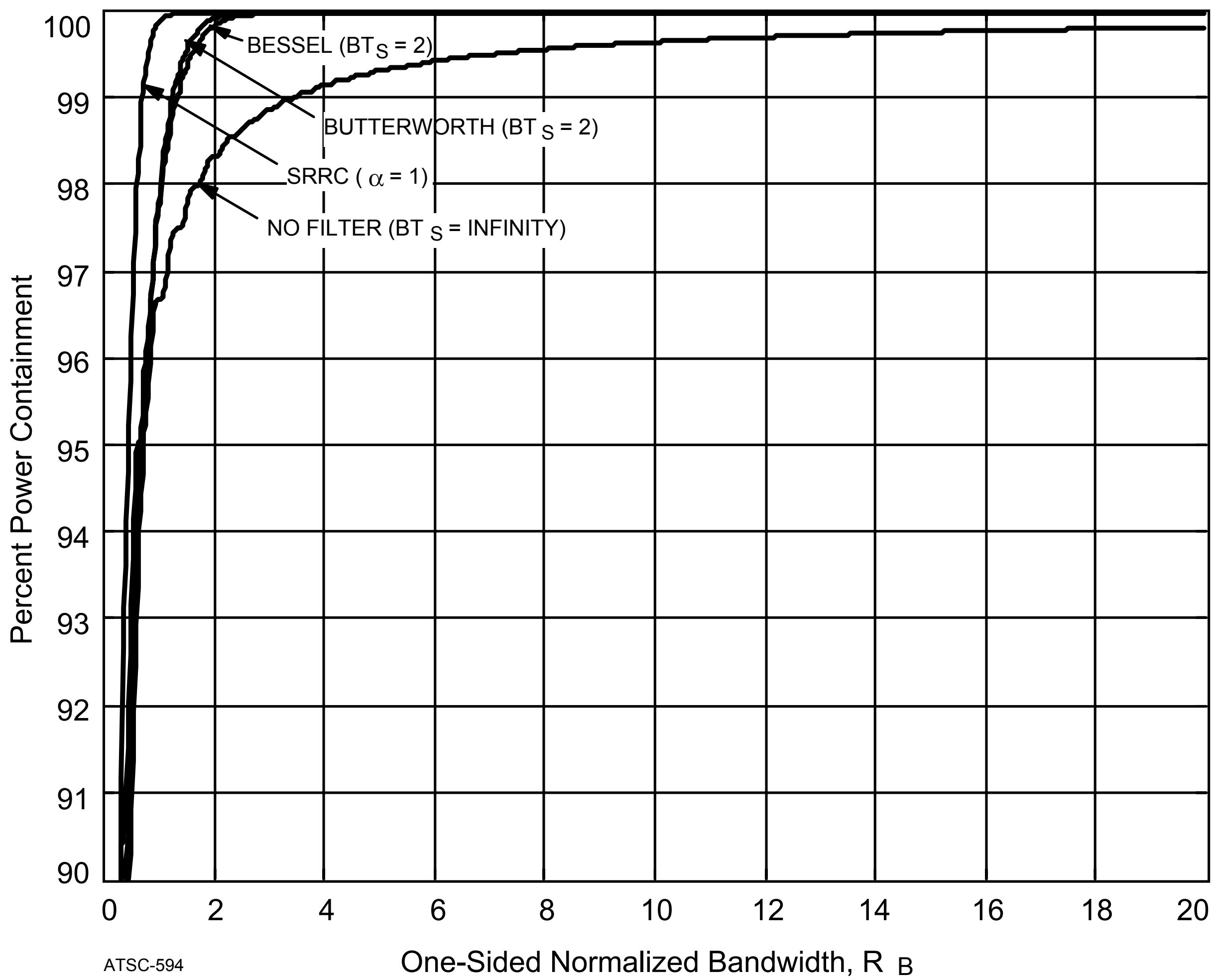


Figure 3.9-3: 8-PSK Modulation Power Containment

3.10 FEHER QPSK (FQPSK)

CCSDS Subpanel 1E (RF and Modulation) became aware of a new modulation type at its Spring 1997 meeting. Named FQPSK for its inventor, Dr. Kamilo Feher, it was reported to have a very narrow RF spectrum and only minimal end-to-end system losses.[14] Test data provided by Dr. Feher showed a spectrum narrower than that of GMSK using a $BT_S = 0.50$ filter. Sideband attenuations were tabulated for the several modulation types studied and it was concluded that FQPSK-B could be a very attractive modulation method.

Subpanel 1E determined that FQPSK deserved further investigation. With Dr. Feher's permission, FQPSK-B, a specific version of FQPSK, was simulated using SPW. Additionally, Mr. Eugene Law of the Naval Air Warfare Center Weapons Division at Point Mugu obtained an FQPSK-B modulator-demodulator (modem) for hardware tests. NASA members of Subpanel 1E witnessed these spectrum tests and obtained copies of the spectra. *Note: This is the only modulation type covered in this report for which there are actual hardware verification tests.* These tests confirm the simulation results reported here.

FQPSK-B modulation is a form of OQPSK modulation in which one of 16 wavelets [waveforms] is selected for transmission on the I-channel and another is chosen for transmission on the Q-channel. Wavelet determination depends on the present and previous data bit pair values for the I and Q channels. There is a ½-symbol-time offset between I and Q transmissions.[15, 16] FQPSK-B modulates and filters at baseband. Thereafter, the signal is translated to an i.f. frequency and then translated again to the transmitted RF frequency.

3.10.1 FQPSK-B Modulation Bit-Error-Rate (BER)

Simulations of FQPSK-B were conducted at JPL with the assistance of Dr. Feher. Figure 3.10-1 shows the Bit-Error-Rate (BER) performance. Like MSK and GMSK modulation, existing transmitting and receiving equipment simulation models were unsuitable for FQPSK-B. However, BER performance was measured using ESA's power amplifier operating in full saturation.

Comparing FQPSK-B to ideal BPSK/NRZ shows that an additional E_B / N_0 of 1.7 dB is required to achieve a 1×10^{-3} BER. This is 0.3 dB greater than GMSK with a $BT_S = 0.5$. Dr. Feher commented that additional system optimization might reduce these losses. His suggestions included adding hard limiters to the transmitting system and improving the receiver filter's phase performance.

Supporting his position, Dr. Feher points to BER measurements made at Point Mugu using actual hardware. Dr. Feher's modem, operating with a 1 Watt SSPA in full saturation, produced a 1×10^{-3} BER at an E_B / N_0 of 8 dB, about 1.3 dB more than ideal BPSK/NRZ and 0.1 dB less than GMSK with a $BT_S = 0.5$. However, that modem was designed for relatively fixed signal level applications, such as closed circuit television distribution. It did not provide 60 dB of sideband attenuation. Further BER tests will be required to verify the better E_B / N_0 performance using a modulator capable of a 60 dB sideband attenuation.

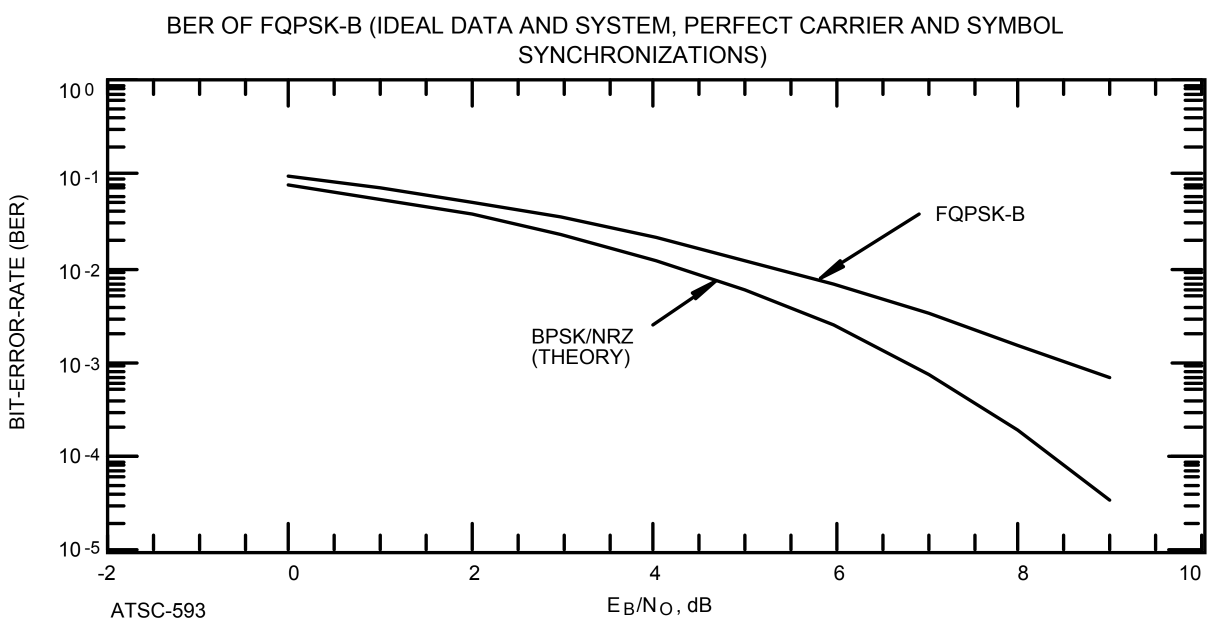


Figure 3.10-1: FQPSK-B Modulation Bit-Error-Rate

3.10.2 FQPSK-B Modulation Spectra

Figure 3.10-2 shows FQPSK-B spectra obtained by simulations. Spectra are obtained using ESA's 10 Watt SSPA operating in full saturation. However, as with the MSK and GMSK simulations, an ideal modulator and receiver were simulated.

FQPSK-B spectra do not have discrete components, giving it a distinct advantage over filtered phase modulation schemes. Sideband attenuation does tend to reach a floor at approximately 75 dB below the peak amplitude where spectral broadening is clearly evident in Figure 3.10-2a. Unlike most of the phase modulation schemes, spectral broadening in the vicinity of f_C does not occur. Rather, Figure 3.10-2a shows the spectrum width around f_C to be significantly narrower than BPSK/NRZ.

FQPSK-B has a very compact, bandwidth-efficient spectrum. Simulations show it to be slightly better than GMSK reaching a level 50 dB below the peak sideband amplitude at a bandwidth of 1.7 R_B rather than at 1.9 R_B for GMSK with a $BT_S = 0.5$. At a sideband attenuation of 60 dB, FQPSK-B and GMSK are within 0.1 R_B of one another.

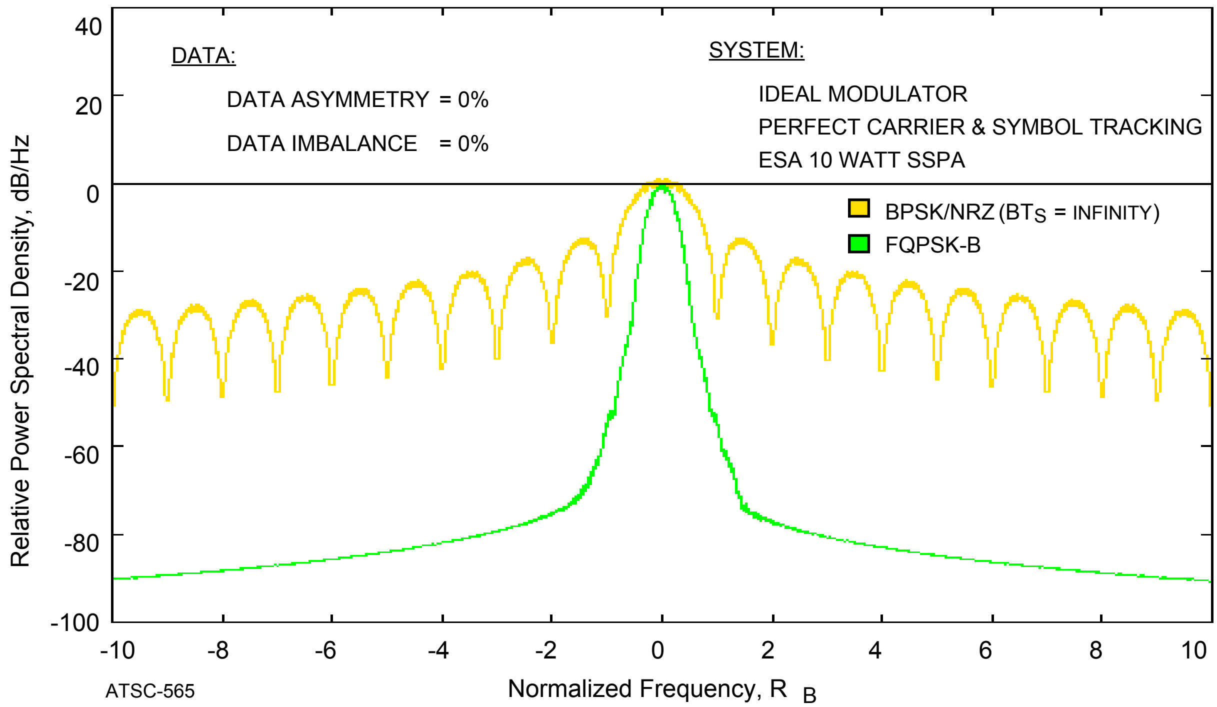
3.10.2.1 Hardware Spectrum Measurements

FQPSK-B is the only modulation type in the Phase 3 *Efficient Modulation Methods Study* for which there are actual hardware measurements. On 1 July 1997 FQPSK-B hardware tests were conducted at the Naval Air Warfare Center at Point Mugu. Dr. Feher contributed a laboratory model of his FQPSK-B modulator. The test configuration included: a random data generator producing 1 Mb/s, Dr. Feher's FQPSK-B modulator, a Hewlett Packard (HP) Model 8780A Vector Signal Generator for QPSK modulation, a frequency translator, a 1-Watt SSPA, and an HP spectrum analyzer.

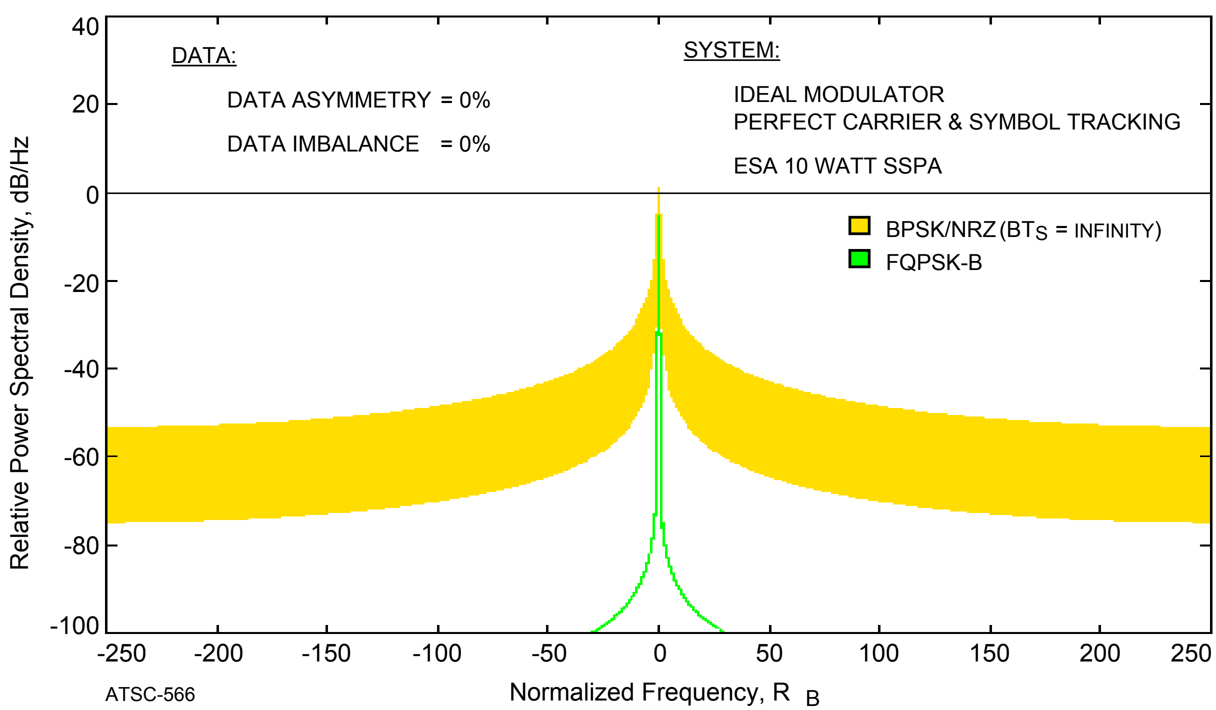
Tests were run with the SSPA in full saturation at 2.44 GHz and frequency spectra were plotted by the HP spectrum analyzer. Figure 3.10-3 reproduces the HP analyzer's plot on the same scale as that used for the *Fine Detail* spectra shown in Figure 3.10-2a. Separate figures are provided because the spectrum plotted in Figure 3.10-3 is virtually indistinguishable from the FQPSK-B curve in Figure 3.10-2a, down to a level 55 dB below the peak sideband amplitude. Below the -55 dB point, the hardware generated spectrum in Figure 3.10-3 becomes wider than the SPW computed spectrum in Figure 3.10-2a. Readers should understand that *no attempt was made to optimize* the hardware test configuration at Point Mugu. The test bed was constructed using hardware elements designed for a variety of other uses.

These measurements confirm the bandwidth efficiency of FQPSK-B modulation, as predicted by SPW. Neither a 2 GHz receiver nor an FQPSK-B demodulator-symbol synchronizer were available to measure Bit-Error-Rate. Therefore, system losses calculated by SPW could not be confirmed using this test configuration.

Additional hardware tests were conducted using an FQPSK-B modem provided by Dr. Feher. The test configuration operated at 70 MHZ. This inexpensive commercially available modem was designed to operate over a more restrictive set of signal levels than the laboratory modulator described above. It did not provide sideband attenuations much below 40 dB.



3.10-2a: Fine Detail ($f_C \pm 10\ R_B$)



3.10-2b: Broadband Spectra ($f_C \pm 250\ R_B$)

Figure 3.10-2: FQPSK-B Modulation Spectra

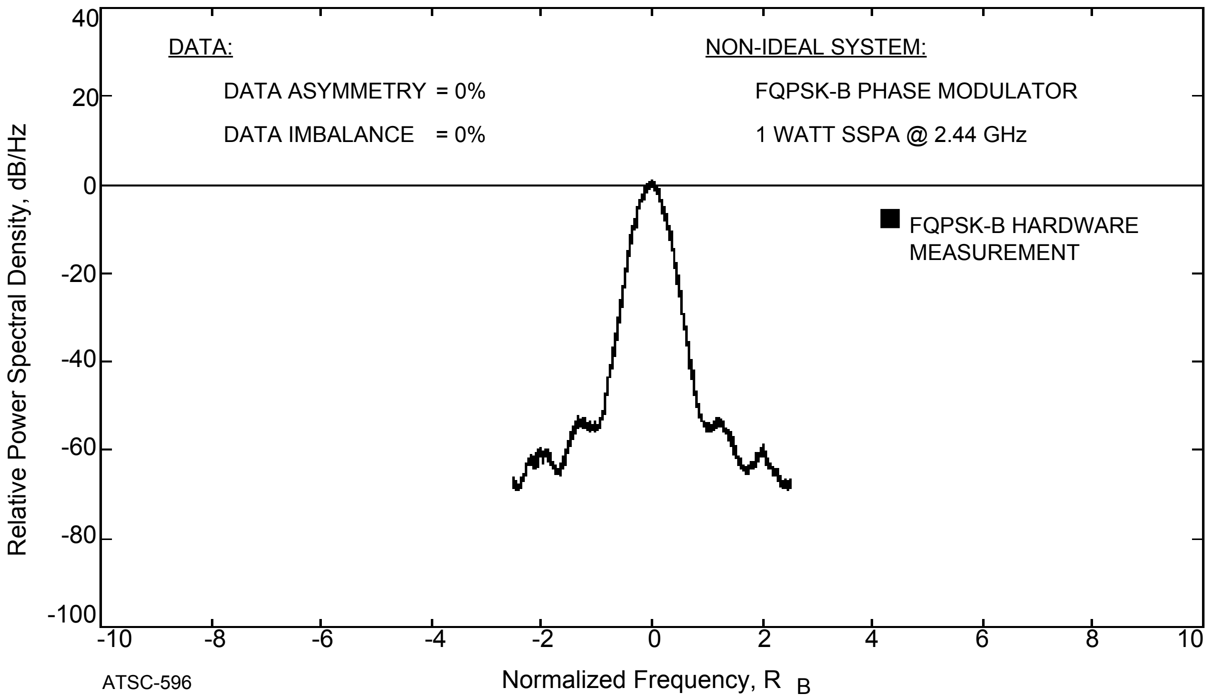


Figure 3.10-3: Hardware Generated FQPSK-B Modulation Spectrum

However, it was possible to make system loss measurements. At a 2 x 10^{-2} BER, the loss was determined to be about 1.3 dB. This tends to corroborate the 1.7 dB loss, computed by SPW, for the better laboratory modulator which has a more restrictive bandwidth.

3.10.3 FQPSK-B Modulation Power Containment

FQPSK-B frequency spectrum efficiency is so high that two power containment plots are required. Figure 3.10-4 is plotted using a 0 - 20 R_B scale for consistency with the other modulation methods. However, virtually all of the transmitted power is contained in such a small bandwidth that Figure 3.10-5 is added. Its scale of 0 - 2 R_B clearly shows the *occupied bandwidth* to be only 0.8 R_B. This is significantly better than the 1.0 R_B found with GMSK using a filter bandwidth of BT_S = 0.5.

3.10.4 FQPSK-B Modulation Study Conclusions

Although FQPSK-B modulation was only recently added to the *Efficient Modulation Methods Study*, it appears to be one of the most bandwidth-efficient modulation method considered. Because of its proprietary nature[17], some of its parameters are not apparent from published documents. Whether this proprietary nature would serve as an impediment to universal application by space agencies is also not clear.

What is clear is that FQPSK-B modulation must be seriously considered for high and very high data rate missions. With RF spectra valued in the Unites States at several hundred dollars per Hertz, NASA, and probably all space agencies, have a duty to investigate this modulation type further.

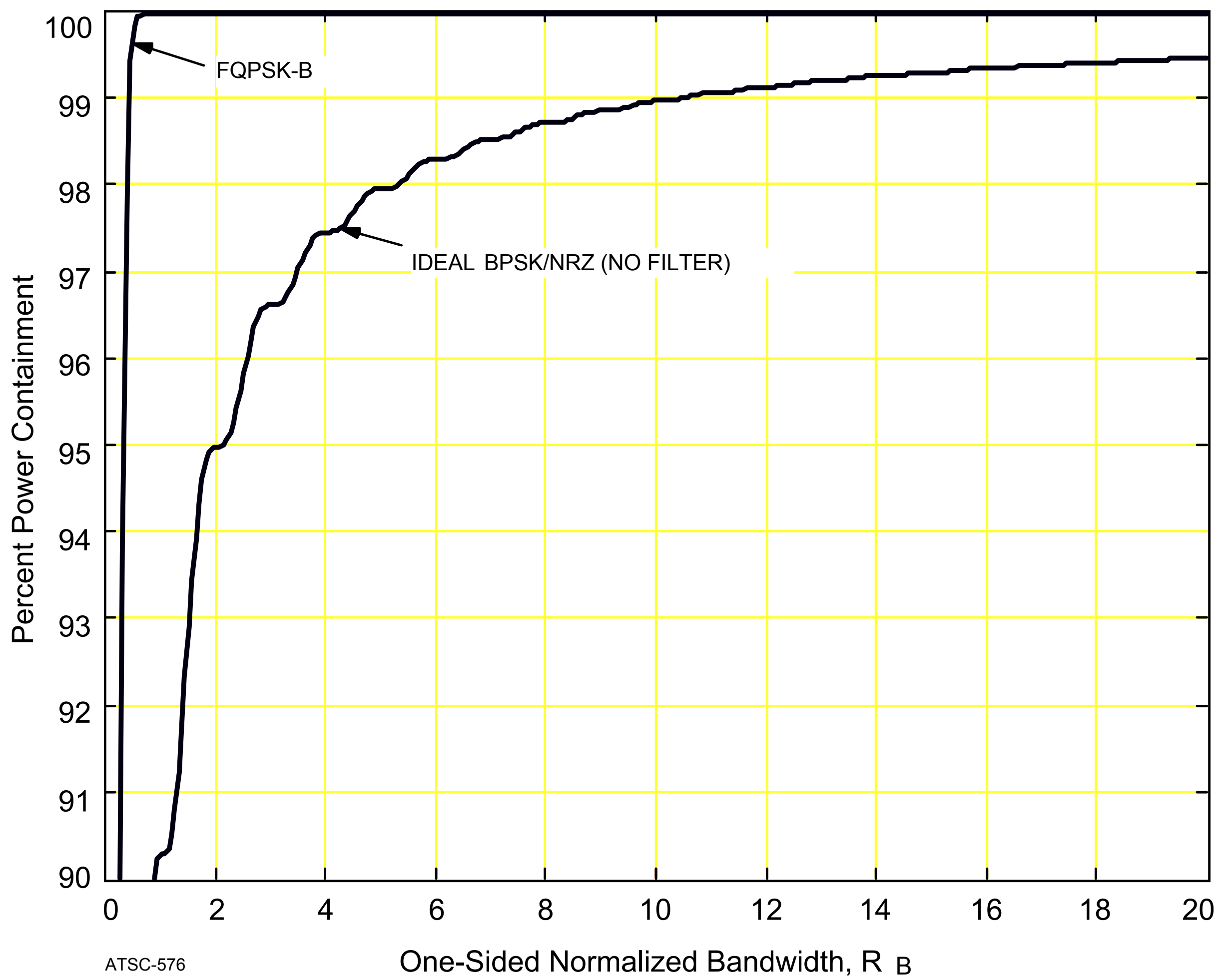


Figure 3.10-4: FQPSK-B Power Containment (0 - 20 R_B)

The authors recommend hardware tests be conducted to verify SPW spectra and BER simulation measurements at the earliest possible time. These tests should include an optimized transmitting and receiving system, capable of measuring both spectra and end-to-end system losses. This test bed should be established in a controlled environment where all parameters can be measured and controlled. If such tests confirm these simulation results, FQPSK-B should be considered as a recommended standard by the CCSDS and SFCG.

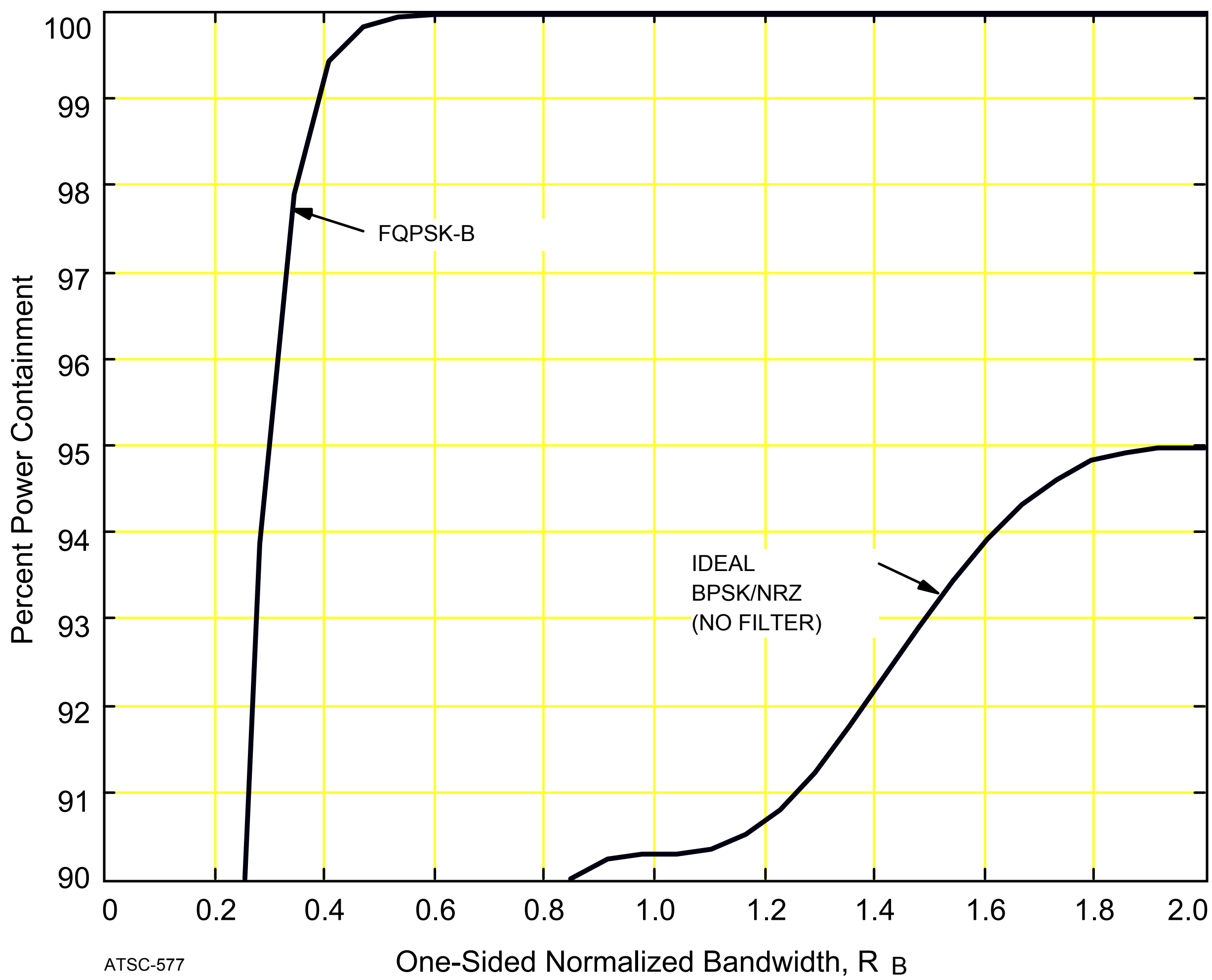


Figure 3.10-5: FQPSK-B Modulation Power Containment (0 - 2 R_B)

4.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The *CCSDS - SFCG Efficient Modulation Methods Study* measured the RF spectrum's width and end-to-end system performance using computer simulations. In compliance with the SFCG's request, the conclusions identify those modulation schemes that are the most bandwidth-efficient and suggest that CCSDS and SFCG Space Agencies adopt recommendations specifying their use.

4.1 SUMMARY

This chapter summarizes the results found in Sections 1, 2 and 3. For each modulation method, it reviews end-to-end system losses, examines RF spectrum bandwidth, and discusses the spectrum improvement factor resulting from baseband filtering.

4.1.1 Summary of Losses

Table 4.1-1 shows system and filtering losses occurring in the end-to-end system for each modulation type. Column 2 contains losses relative to ideal BPSK/NRZ modulation. Recall that ideal BPSK/NRZ assumes: perfect data ($P_m = P_s = 0.5$; 0 =0), an ideal system (perfect carrier tracking and symbol synchronization), and no filtering (BT = 4).

Existing SPW models for the ARX II receiver were unable to handle 8-PSK, MSK, GMSK, and FQPSK modulation. Except for the SSPA, which was identical to that for the other modulation types, ideal system hardware was used for simulating performance making it impossible to determine carrier tracking and synchronization losses. RF spectrum width was measured as were end-to-end losses relative to ideal BPSK/NRZ. Filtering losses, inherent in GMSK and FQPSK-B, are included in leftmost column of Table 4.1-1 containing losses relative to ideal BPSK/NRZ. **NOTE: All modulation types exhibit a loss with respect to ideal BPSK/NRZ. To find the true cost of a modulation method, one should subtract 0.56 dB which is the loss for filtered BPSK. Thus, the true loss for GMSK (BT_S = 0.5) is about 0.8 dB and FQPSK-B is about 1.1 dB.**

Phase 3 studies employed baseband filtering exclusively. A principal objective was the selection of the proper filter bandwidth. Recall that filter selection criteria required using a filter producing the narrowest RF spectrum while introducing only moderate losses.

From Table 4.1-1, it is clear that filters having a $BT_S = 1$ often exceeded the allowable loss of approximately 1 dB. However, filters having a $BT_S = 2$ generally met the 1 dB loss criterion. 8-PSK was the exception requiring a $BT_S = 3$ filter bandwidth to be acceptable. For the other modulation types, BER curves in Section 3 showed that there was no significant benefit in using a $BT_S = 3$ filter bandwidth. Thus, Butterworth and Bessel baseband filters, with a $BT_S = 2$, were used.

4.1.2 RF Spectrum Efficiency

Another Phase 3 study objective was to determine the RF spectral bandwidth of each modulation type. This was necessary to rank the several modulation methods with respect to one-another. Many Spectrum Managers are concerned principally with *occupied bandwidth* (i.e., 99% power containment). Here, the focus is on many power containment levels.

Table 4.1-1: System Losses

Modulation Type	Losses in dB (Non Ideal Data and System) [1]							
	Loss Relative to Ideal BPSK [2]	Butterworth Filter (3^{RD} Order)			Bessel Filter (3^{RD} Order)			SRRC Filter
		Filtering Losses [3]			Filtering Losses [3]			Filtering Loss [3]
		BT=1	BT=2	BT=3	BT=1	BT=2	BT=3	"=1
PCM/PM/NRZ	-1.52	-0.7	-0.20	-0.01	-0.80	-0.10	-0.01	-0.52
PCM/PM/Bi-N	-0.56	-1.1	-0.34	-0.12	-0.91	-0.16	-0.01	-0.45
BPSK/NRZ	-0.56	-0.9	-0.30	-0.12	-0.70	-0.17	-0.01	-0.57
BPSK/Bi-N	-0.61	-1.0	-0.44	-0.25	-0.87	-0.29	-0.11	-0.79
QPSK/NRZ	-0.64	-2.92	-0.82	-0.37	-2.24	-0.60	-0.20	-3.70
OQPSK/NRZ	-0.65	N/A [4]	-1.30	-0.37	N/A [4]	-1.00	-0.23	N/A [4]
MSK [5]	-0.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GMSK [5, 6]	-0.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A
GMSK [5, 7]	-1.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8-PSK	-3.4	N/A [4]	-1.9	-0.9	N/A [4]	-2.4	-1.0	N/A
FQPSK-B [5]	-1.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A

NOTES:

1. **Losses determined at a Bit-Error-Rate of 1 x 10^{-3} with 0 = 0, P_m = 0.55 (negative numbers indicate a loss).**
2. **System losses were measured relative to ideal BPSK/NRZ (perfect data, lossless equipment).**
3. **Filtering Losses include: ISI + Mismatch + Imperfect Carrier Tracking & Symbol Synchronization.**
4. **BER reached a minimum of 1 x 10^{-2}.**
5. **Filtering Losses Not Available (N/A) because BER measured with ideal system components.**
6. **Filter bandwidth BT_S = 1 (BT_B = 0.5).**
7. **Filter bandwidth BT_S = 0.5 (BT_B = 0.25).**

The *Efficient Modulation Methods Study* was motivated by a desire to pack a substantially greater number of spacecraft into a given frequency allocation, particularly in the 2 and 8 GHz Category A mission bands. Maximum packing density occurs when spectra from two spacecraft, operating on adjacent frequencies, just begin to overlap at n dB below the peak of the data sideband's spectrum.

This follows from a *worst-case* assumption that the Earth station's antenna is boresighted on both spacecraft simultaneously. Where spacecraft are not coincidently within the Earth station antenna's beamwidth, the interferer's and victim's relative signal strengths will determine the spacial separation necessary to avoid interference. Obviously, even as frequency band usage increases, some spacial separation is expected. This study attempted to determine the value of n.

Views differ regarding the optimal value of n. Some believe that spectra from spacecraft on adjacent frequencies could be permitted to intersect at a level of 20 dB below the peak sideband amplitude. Others believe that the number should be greater or less than 20 dB.

In any event, Category A missions in highly elliptical orbits can undergo signal level changes of 30 dB or more at the Earth's surface. Thus, it would seem prudent to prohibit RF spectra, from spacecraft operating on adjacent frequencies, from intersecting at levels higher than 50 dB below the peak of the data sideband generated by the spacecraft having the stronger signal.

To provide maximum flexibility, RF spectrum bandwidths have been tabulated at values of n from 20 to 60 (dB) below the data sideband's peak. RF spectrum width increases as a function of n and each user must select the proper value. A value of n = 50 is recommended for most applications.

For a specific value of n, one can calculate the improvement in spectral efficiency. CCSDS Subpanel 1E concluded that BPSK/NRZ was to be the reference modulation type. A *Spectrum Improvement Factor* (*SIF*) can be calculated by comparing the bandwidth of unfiltered BPSK/NRZ to the bandwidth of the modulation method under discussion according to the relationship:

$$SIF = \frac{Bandwidth\ \ of\ \ Unfiltered\ \ BPSK/NRZ}{Bandwidth\ \ of\ \ Named\ \ Modulation\ \ Type} \tag{4-1}$$

Since the bandwidth is a function of n, the SIF will also vary with n. Table 4.1-2 contains the bandwidths and *SIF*s at several values of n for all modulation types covered in this Phase 3 study. Bandwidths for all phase modulation types were evaluated using a Butterworth, $BT_S = 2$ filter.

For symmetrical data (0=0), no spikes are present in the spectra of unfiltered BPSK/NRZ. All measurements in Table 4.1-2 were made with respect to a continuous unfiltered BPSK/NRZ reference spectrum. Conversely, all phase modulation schemes, which employ baseband filtering, have both continuous and discrete parts to their spectrum.

SIF measurements in Table 4.1-2 were made with respect to the discrete part of the baseband filtered modulation spectrum. This represents a *worst case* bandwidth comparison. Readers should understand that no discrete spectral components exceed the value of n in any of the *SIF*s shown in Table 4.1-2. Since SPW's resolution bandwidth was set to 1.33 Hz, one can conclude that the *SIF*s should be close to those obtained using real hardware viewed on a spectrum analyzer with a 1 Hz resolution.

Preferred modulation types become immediately apparent when SIFs are plotted as a function of n as in Figure 4.1-1. Modulation types fall into two distinct groups FQPSK-B / GMSK and everything else. Even 8-PSK is not a competitor for those two types. The message is clear:

> ***If RF bandwidth is important, then the results of this study show that FQPSK-B and GMSK (BT_S = 0.5) are the modulation methods of choice.***

Table 4.1-2: Bandwidth Efficiencies

	Two-Sided Bandwidth, R_B						Spectrum Improvement Factors [2]				
Modulation Type	Sideband Attenuation, dB						Sideband Attenuation, dB				
	20	30	40	50	60		20	30	40	50	60
PCM/PM/NRZ [1]	8.2	10.2	10.2	14.2	16.2		1.3	2.3	7.3	18.4	40.2
PCM/PM/Bi-N [1]	16.2	20.2	24.2	28.2	32.2		0.7	1.2	3.1	9.3	20.2
BPSK/NRZ [1]	8.2	10.2	14.2	16.2	18.2		1.3	2.3	5.3	16.1	35.8
BPSK/Bi-N [1]	20.2	24.2	28.2	32.2	40.2		0.5	1.0	2.6	8.1	16.2
QPSK [1]	5.2	6.2	7.2	8.2	12.2		2.1	3.7	10.4	31.8	53.4
OQPSK [1]	5.2	7.2	8.2	10.2	18.2		2.1	3.2	9.1	25.6	35.8
MSK	1.3	3.0	5. 1	9.1	19.1		8.3	7.7	14.7	28.7	34.1
GMSK (BT_S=1)	1.2	1.9	2.3	2.5	3.0		9.0	12.2	32.5	104.4	217.0
GMSK (BT_S=0.5)	1.0	1.2	1.6	1.9	2.1		10.8	19.3	46.8	137.4	310.0
8-PSK [1]	3.6	4.8	5.6	6.8	8.8		3.0	4.8	13.4	38.4	74.0
FQPSK-B	0.9	1.1	1.4	1.7	2.2		12.0	21.1	53.4	153.5	295.9
Average	**6.5**	**8.2**	**9.8**	**11.9**	**15.7**		**4.2**	**6.6**	**16.6**	**47.6**	**94.4**

NOTES:
1. **Measurements of phase modulated spectra are made using Butterworth BT_S = 2 filter**
2. **Measurements show bandwidth improvement compared to unfiltered BPSK/NRZ modulation**

Further work is required to determine Filtering Losses of FQPSK-B and GMSK modulation types. Losses should be determined by actual hardware tests rather than by additional simulations. Currently, there is a plan to conduct hardware tests with several modulation types, including FQPSK-B, at ESA/ESTEC in early 1998. Such tests can be used to validate the information contained in this report.

Relative bandwidth efficiencies can also be shown by plotting the Two-Sided Bandwidth (R_B) as a function of Sideband Attenuation (dB). Figure 4.1-2 graphically illustrates the performance of the 10 modulation methods studied. Although less dramatic than Figure 4.1-1, Figure 4.1-2 clearly demonstrates that there are three classes of bandwidth efficiency. Ranked from highest to lowest bandwidth efficiency, these are:

1. FQPSK-B and GMSK
2. BPSK/NRZ, PCM/PM/NRZ, OQPSK, QPSK, MSK and 8-PSK
3. BPSK-N and PCM/PM/Bi-N

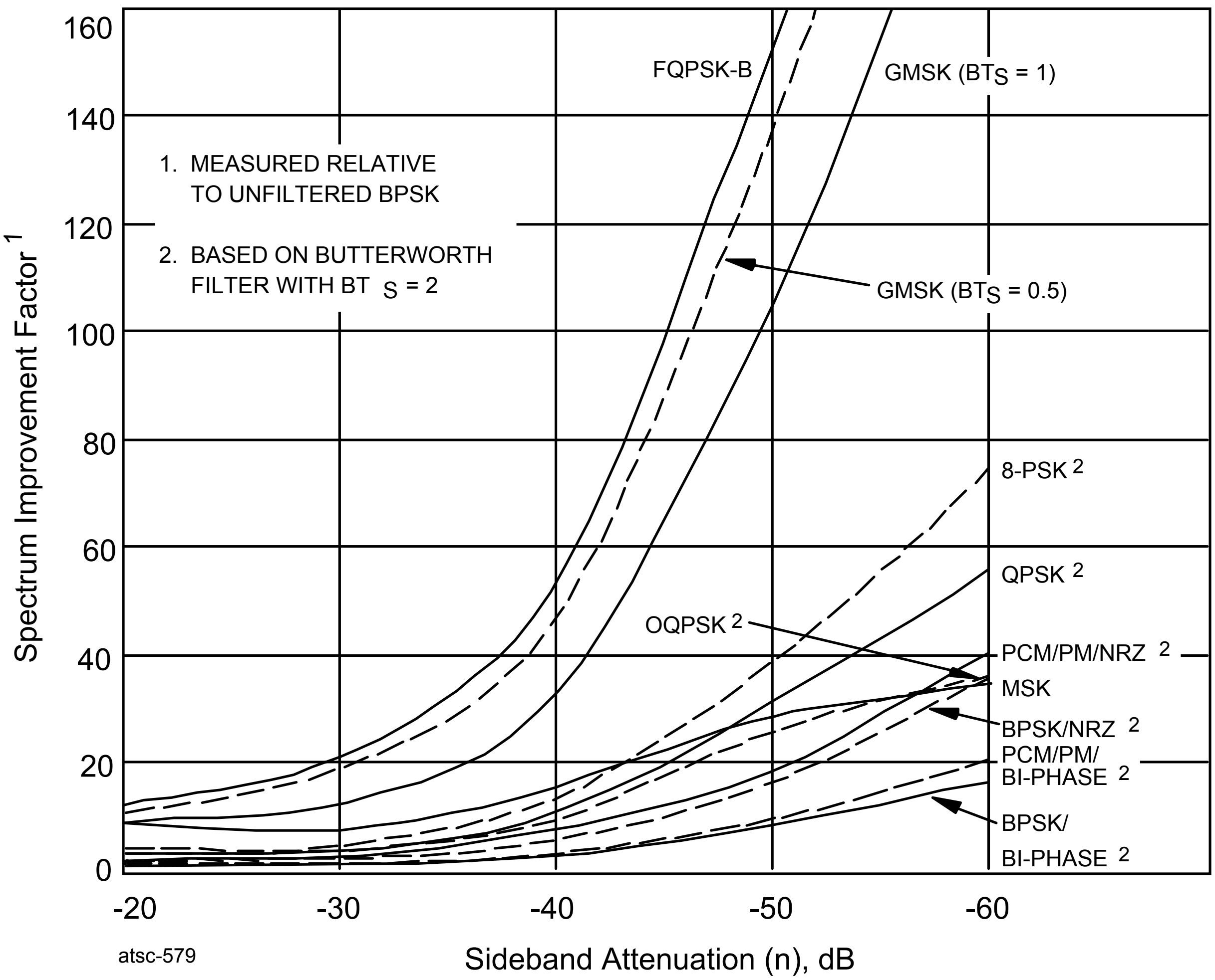


Figure 4.1-1: Spectral Efficiency Relative to Unfiltered BPSK / NRZ

Figure 4.1-1 relates the spectral efficiencies of the several modulation methods investigated in the Phase 3 *Efficient Modulation Methods Study*. *SIF*, as defined in equation 4-1 is plotted as a function of n (number of dB below the peak sideband amplitude). Three classes of bandwidth efficiency are evident: High (FQPSK-B and GMSK); Medium (8-PSK, QPSK/OQPSK, MSK, PCM/PM/NRZ, and BPSK/NRZ); and Low (PCM/PM/Bi-N, BPSK/Bi-N).

All Phase 3 modulation bandwidth measurements are made using a Butterworth 3[RD] order BT_S = 2 filter. MSK has no filtering and GMSK curves are labeled with the Gaussian filter's BT_s factor. FQPSK-B measurements are based on a proprietary filter in FQPSK-B modulation.

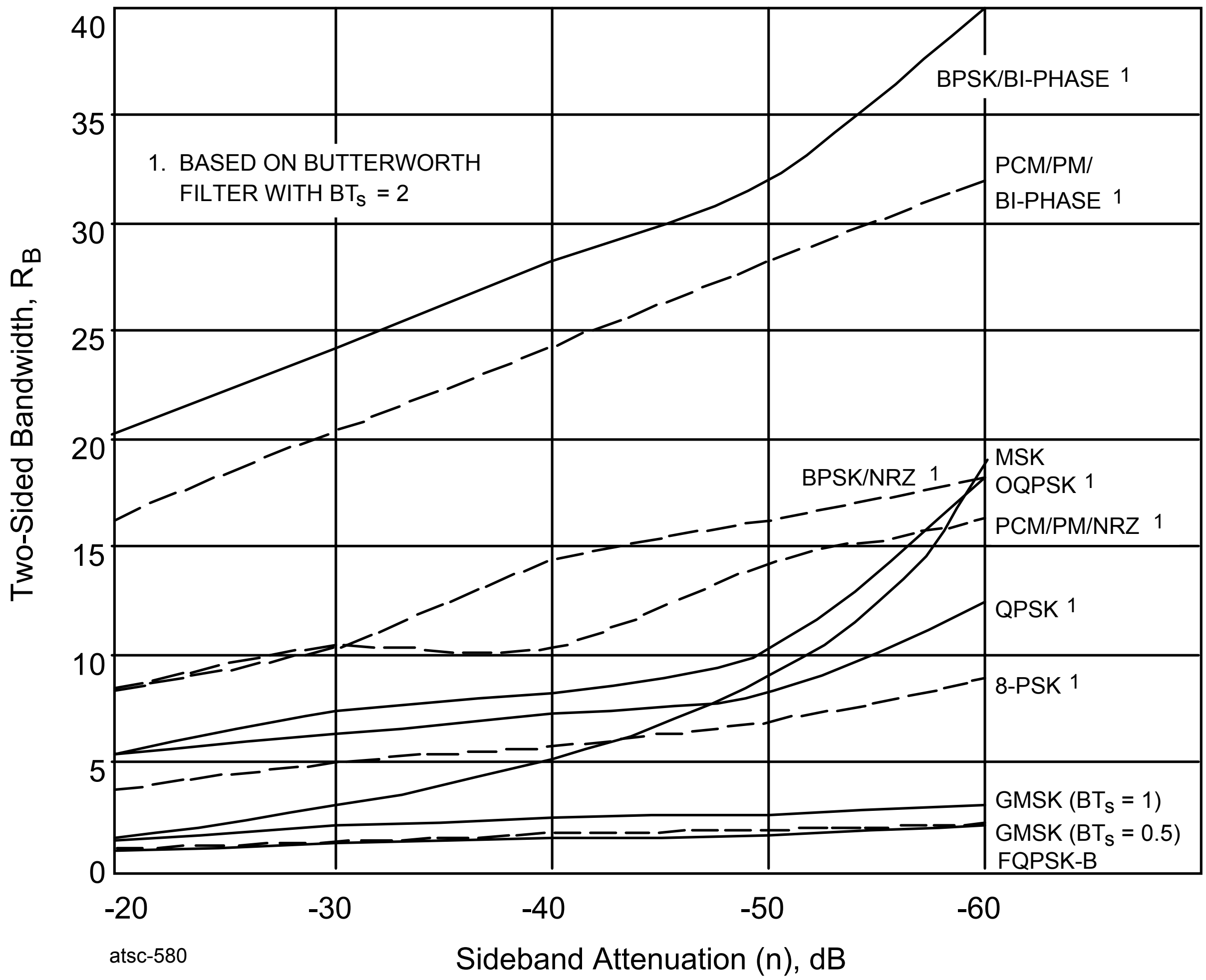


Figure 4.1-2: Two-Sided Required Bandwidth

Figure 4.1-2 depicts modulation efficiency using the Two-Sided Bandwidth as the key parameter. It shows the RF bandwidth *required* by each modulation type to obtain a desired value of n. This Figure can be used to establish the separation between adjacent users operating in the same frequency band, as well as to make a cost comparison between alternative modulation methods.

For example, at n = - 50 [dB], adjacent users *require* a separation of only 2 times their data bit rate when FQPSK-B modulation is used, whereas a separation of 32 times the data bit rate is *required* when BPSK/Bi-N modulation is employed. The 16-fold difference between the most and least efficient modulation methods facilitates an easy cost-comparison of the several modulation methods in this study.

Costs can be calculated if the spectrum's unit-value (<) is known. Auctions of the 900 MHZ band, conducted by the Federal Communications Commission several years ago, yielded an average return of < = $744/Hz. Modulation method cost comparisons can be made using the following relationship:

Cost = < • Data rate (Hz) • Required Two-Sided Bandwidth from Figure 4.1-2. (4-2)

4.2 CONCLUSIONS

Conclusions fall into distinct categories relating to filtering methods, losses, modulation types, and *Spectrum Improvement Factors (SIFs)*. Each conclusion is summarized in the subsections below.

4.2.1 Filtering Conclusions

Baseband filtering significantly reduces the transmitted RF spectrum's width. Study conclusions are:

- Filtering of transmitted signals will be required to obtain an acceptably narrow RF spectrum.
- Hardware limitations make post PA filtering impractical at data rates below about 8 Ms/s.
  - Realizable *Q*s limit the filter's bandwidth to about 1-2% of the transmitted frequency.
  - Filtering power losses may be unacceptable, even at a 1-2% bandwidth.
  - For low data symbol rates, post PA filtering <u>may</u> make turnaround ranging difficult.
- Depending upon its architecture, transponder i.f. filtering may <u>not</u> be practical.
  - *Q* limitations stated above apply if modulation occurs at the transmitting frequency.
  - Filtering at i.f. requires transponders be modified for each mission.
  - Filtering at i.f. makes data rate changes difficult.
  - For low data symbol rates, i.f. filtering <u>may</u> make turnaround ranging difficult.
  - Filtering within the transponder risks introducing spurious emissions causing *lock-up*.
- Baseband filtering is the only practical alternative to unacceptable post PA and i.f. filtering.
  - Baseband filtering can be accomplished with a simple, passive low-pass filter design.
    - A 3[RD] order Butterworth filter ($BT_S = 2$) provides the best performance-simplicity ratio.
  - Filtering prior to phase modulation produces undesirable spikes in the RF spectrum.
    - Spikes can only be avoided by using a different modulation method (GMSK, FQPSK).
- Both GMSK and FQPSK-B utilize baseband filtering and do not require i.f. nor post PA filters.

4.2.2 Loss Conclusions

Table 4.1-1 partitions losses into two categories: System (losses relative to ideal BPSK) and Filtering (ISI and Mismatch). One criterion for the Phase 3 study was that end-to-end losses should be *reasonable*. CCSDS Subpanel 1E determined that approximately 1 dB was reasonable. The following conclusions regarding losses were reached:

- High system loss (1.5 dB) found for PCM/PM/NRZ, resulted from a 10% data imbalance.
  - When a $BT_S = 2$ Butterworth filter is used, data imbalance should not exceed 5%.
- 8-PSK modulation exhibits an excessive system loss (3.4 dB).
  - Filtering losses decreased for non-constant envelope modulation.
    - However, spectrum width increased.
    - Losses were not reduced to an acceptable level.
  - High losses make 8-PSK modulation unsuitable for power-limited Category A missions.
- GMSK ($BT_S = 0.5$) also exhibited high (1.4 dB) system losses.
  - Increasing filter bandwidth to $BT_S = 1$ reduced system losses to an acceptable level.
  - Losses were measured with an ideal (lossless) receiver.
- FQPSK-B losses were found to be a high 1.7 dB.
  - Losses were also measured with an ideal (lossless) receiver.

4.2.3 Modulation Methods Conclusions

Figures 4.1-1 and 4.1-2, graphically identify the preferred modulation methods. For the several modulation methods considered, the following conclusions were reached.

- FQPSK-B provides the narrowest RF spectrum of all modulation methods studied.
  - FQPSK-B should be considered for all high and very high data rate missions.
    - Provided that losses are acceptable.
- GMSK, with a filter bandwidth $BT_S = 0.5$, produces virtually equivalent results to FQPSK-B.
  - Further work is required to validate system losses using real hardware.
- 8-PSK, with its high losses, does not appear useful for most Category A missions.
  - Excessive losses and modest performance gains do not provide sufficient advantages.
- QPSK has comparatively poorer bandwidth efficiency than does FQPSK-B and GMSK.
  - Its common usage may dictate its consideration in some applications.
  - Absent spread spectrum, QPSK cannot provide simultaneous telemetry and ranging.
- OQPSK could not be evaluated properly with the UPM.
  - OQPSK should be reserved for applications requiring separate, independent data channels.
  - Orthogonally phased BPSK/NRZ modulators, with a ½ symbol offset should be used.
- BPSK/NRZ has poor bandwidth efficiency and should not be used if bandwidth is important.
  - Bandwidth efficiency is slightly lower than PCM/PM/NRZ modulation.
  - BPSK/NRZ may be an alternative to PCM/PM/NRZ when:
    - A residual carrier is not required.
    - The data imbalance is so great that PCM/PM/NRZ would suffer excessive losses.
- PCM/PM/NRZ has poor bandwidth efficiency, but has best efficiency of residual carrier types.
  - Applications requiring a residual carrier should consider this modulation method.
  - When using PCM/PM/NRZ, care must be taken to ensure proper data balance.
- MSK modulation is not highly spectrum efficient.
  - No specific advantages were found to MSK, save the lack of spectral spikes.
- Bi-N modulation has very poor RF spectrum efficiency.
  - Bi-N modulation should not be used unless the symbol transition density is too low.
  - This conclusion applies to both PCM/PM/Bi-N and BPSK/Bi-N modulations.
- Subcarrier modulation tends to waste spectrum and should be avoided whenever possible.
  - When used, the subcarrier frequency-to-data symbol rate ratio should be low (# 4).
  - CCSDS *virtual channels* should be used to separate data types.

4.2.4 Spectrum Improvement Conclusions

The following conclusions were reached regarding RF spectrum efficiency improvement:

- Baseband filtering greatly increases the number of spacecraft operating in a frequency band.
  - Spectrum utilization efficiency can increase by a factor from 2 to more than 100 times.
  - The amount of improvement depends upon modulation method and sideband attenuation.
  - This result attains despite non-linear system elements, non-ideal data, and spectral spikes.
- Modulation method should be selected to maximize the *Spectrum Improvement Factor*.
  - Modulation schemes with low *Spectrum Improvement Factors* should be avoided.
  - Modulation method selection should be based on system capabilities, data rates, and *SIF*s.

4.3 RECOMMENDATIONS

Based upon the results of the Phase 3 *Efficient Modulation Methods Study*, the CCSDS and SFCG are encouraged to create and adopt Recommendations specifying the preferred modulation methods. Because space missions have a broad range of objectives, communication requirements will vary. Some grouping of applications is necessary before assigning a modulation type.

4.3.1 Mission Classification

One method for grouping applications is by specific attributes. Missions sharing those attributes are assigned a classification and a modulation method(s) most appropriate to that group are selected. Where RF spectrum and modulation types are of paramount concern, the telemetry data symbol rate appears to be the best discriminator. The following classifications are recommended:

4.3.1.1 *Low Data Rate (10 s/s - 20 ks/s)*

This class includes low rate scientific missions as well as the Telemetry, Tracking, and Command (TT&C) services for most missions. Turnaround ranging may be required. If it is, subcarrier modulation may be appropriate (see CCSDS Recommendation 401 (3.3.4) B-1). If ranging is not required, then any appropriate modulation type should be acceptable. All mission types operating in the space services can be found in this class.

4.3.1.2 Modest Data Rate (20 ks/s - 200 ks/s)

Most Category A missions fall in this and the following classification. If space agencies are serious about reducing RF spectrum requirements, they must use appropriate filtering and modulation techniques for spacecraft in these classes. Typical missions operate in the *Space Research* service and include NASA's ISTP Wind and ESA's Integral missions.

The recommended modulation method depends upon whether or not simultaneous telemetry and turnaround ranging signals are required (see CCSDS Recommendation 401 (3.4.1) B-1). If they are, a residual carrier modulation method is suggested because users can independently control the division of power between the carrier, telemetry, and ranging channels. PCM/PM/NRZ is the most bandwidth-efficient residual carrier modulation method and is recommended provided that the telemetry data imbalance is less than 5% during a time interval equal to one time-constant of the Earth station receiver's phase-locked-loop.

At low data symbol rates, care must be taken with PCM/PM/NRZ modulation to ensure that the Earth station's receiver can distinguish between the RF carrier and the spectral components of the data sidebands. The spacecraft's modulation index and the Earth station receiver's phase-locked-loop bandwidth should be adjusted to ensure proper operation.

If simultaneous telemetry and turnaround ranging is required and the data imbalance is greater than 5%, then Unbalanced QPSK (UQPSK) is the recommended modulation type. Within limits, telemetry and ranging powers can be set independently. If simultaneous telemetry and turnaround ranging is not required or where data imbalance exceeds 5%, BPSK/NRZ is recommended.

4.3.1.3 *Medium Data Rate (200 ks/s - 2 Ms/s)*

As noted, most Category A scientific missions fall into this and the prior classification. Generally, such spacecraft operate in the *Space Research* service allocation. Examples include NASA's Polar and ESA's SOHO missions.

Because many of these missions are collecting scientific data, simultaneous turnaround ranging is frequently required. In these cases, PCM/PM/NRZ modulation is recommended, providing the telemetry data symbol imbalance does not exceed 5% in one time-constant of the Earth station receiver's phase-locked-loop. If data imbalance exceeds 5%, then UQPSK can be used.

In this classification, data symbol rates can be as high as 2 Ms/s, so bandwidth conservation is important. If simultaneous turnaround ranging is not required, then QPSK modulation is recommended.

4.3.1.4 *High Data Rate (2 Ms/s - 20 Ms/s)*

Typically, missions with data symbol rates in this range operate in the *Earth Exploration Satellite* service. Examples include NASA's Lewis and the Canadian Space Agency's (CSA's) Radarsat projects. In this and the following classification, RF spectrum limiting becomes imperative. Decreasing bandwidth utilization by a factor of 10 saves considerably more RF spectrum when the data symbol rate is 20 Ms/s than is the case when it is 200 ks/s. Both the CCSDS and SFCG should immediately adopt filtering and modulation Recommendations for these last two classes.

From Figures 4.1-1, 4.1-2, and Table 4.1-1, FQPSK-B or GMSK ($BT_S = 0.5$) modulation are the clear choices if RF spectrum conservation is important. Modulator modifications may be required to provide turnaround ranging with either of these modulation types and the ranging signal will have to be sequential, not simultaneous, with the telemetry data.

4.3.1.5 *Very High Data Rate (20 Ms/s - and Above)*

Missions with data symbol rates in this range operate almost exclusively in the *Earth Exploration Satellite* service. Examples include NASA's Earth Observation Satellite (EOS) and ESA's Earth Resources Satellite (ERS-1). Previous comments regarding bandwidth conservation and modulation methods apply emphatically to this class. FQPSK-B or GMSK ($BT_S = 0.5$) are the recommended modulation methods.

The CCSDS and SFCG are urged to move with all dispatch to obtain the additional system performance information for both FQPSK-B and GMSK modulation types. The authors recommend that tests, using real hardware, be conducted in a carefully controlled environment to validate these simulations and to measure actual system performance. Recommendations, consistent with Table 4.3-1, should be adopted at the earliest possible opportunity.

Table 4.3-1: Recommended Modulation Methods for Category A Missions

No.	Telemetry Classification	Classification Attributes	Example Missions	Recommended Modulation Method
1	Low Data Rate 10 s/s - 20 ks/s	Simultaneous telemetry & ranging may be required.	TT&C, Low Rate Science	PCM/PSK/PM (Sine) Any Appropriate Type
2	Modest Data Rate 20 ks/s - 200 ks/s	Simultaneous telemetry & ranging required Data Imbalance # 5%	*Space Research* NASA/Polar ESA/Integral	PCM/PM/NRZ UQPSK [1]
		Simultaneous telemetry & ranging not required Data Imbalance $ 5%	*Space Research* CNES/SPOT-4	BPSK/NRZ
3	Medium Data Rate 200 ks/s - 2 Ms/s	Simultaneous telemetry & ranging required Data Imbalance # 5% (If $ 5%, use UQPSK)	*Space Research* NASA/Polar	PCM/PM/NRZ UQPSK [1]
		Simultaneous telemetry & ranging not required	NASA/Image	QPSK
4	High Data Rate 2 Ms/s - 20 Ms/s	Simultaneous telemetry & ranging not required	*Space Research* NASA/Lewis	FQPSK [2] GMSK [2]
5	Very High Data Rate 20 Ms/s and Above	Simultaneous telemetry & ranging not required	*EES* NASA/EOS-AM	FQPSK [2] GMSK [2]

NOTES:
1. **UQPSK should be used where the Data Imbalance $ 5% or when data rates are so low that carrier tracking loop interference can occur.**
2. **Subject to confirmation of reasonable end-to-end system losses.**

GLOSSARY

ARX II	A Research and Development Earth Station Receiver, (Prototype for DSN Block V)
BER	Bit-Error-Rate
Bi-N	Binary-Phase [Manchester] modulation
B_L	Receiver phase-locked-loop's bandwidth, expressed in Hz
BPSK	Bi-Phase Shift Keying [modulation method]
BT_B	Bandwidth • Time Product Based on Bit-Period
BT_S	Bandwidth • Time Product Based on Symbol-Period
Category A	A Space Mission whose distance from Earth is less than $2 \cdot 10^6$ km
CCSDS	Consultative Committee for Space Data Systems
DSN	Deep Space Network
DTTL	Digital Transition Tracking Loop
ESA	European Space Agency
ESOC	ESA Operation Center (Darmstadt, Germany)
ESTEC	ESA Technical Center (Noordwijk, The Netherlands)
FQPSK	Feher QPSK [modulation method]
GMSK	Gaussian Minimum Shift Keying
HP	Hewlett Packard
Hz	Hertz
k	Kilo (1,000)
kb/s	Kilo Bits per Second
kHz	Kilo Hertz
ks/s	Kilo Symbols Per Second
M	Mega (1,000,000)
MHZ	Mega Hertz
MAP	Maximum A Posteriori
MODEM	Modulation-Demodulation
MSK	Minimum Shift Keying
NRZ	Non Return to Zero [format]
OQPSK	Offset QPSK [modulation method]
PA	Power Amplifier
PCS	Personal Communications System
PM	Phase Modulation
PSK	Phase Shift Keying
P_T	Total Power [transmitted]
QPSK	Quadrature Phase Shift Keying [modulation method]
SAW	Surface Acoustic Wave [Filter]
SER	Symbol-Error-Rate
SFCG	Space Frequency Coordination Group
SPW	Cadence Design Systems Inc. Signal Processing Worksystem
SRRC	Square Root Raised Cosine [Filter]
SSPA	Solid State Power Amplifier
Subpanel 1E	CCSDS group concerned with RF and Modulation standards
$-_M$	Probability of a Mark [+ 1]
$-_S$	Probability of a Space [- 1]

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